PB89-189856

Application Guide for the Source PM10 Exhaust Gas Recycle Sampling System

Southern Research Inst., Birmingham, AL

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

Apr 89

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA/600/3-88/058

2.

3. RECIPIENT'S ACCESSION NO.
PB89 189856/AS

4. TITLE AND SUBTITLE
Application Guide for the Source PM-10 Exhaust Gas Recycle Sampling System

5. REPORT DATE
April 1989

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Randal S. Martin, S.S. Dawes, A.D. Williamson, W.E. Farthing

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Southern Research Institute
Birmingham, AL 35255

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
68-02-4442

12. SPONSORING AGENCY NAME AND ADDRESS
Atmospheric Research and Exposure Assessment Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This document describes assembly, operation, and maintenance of the Exhaust Gas Recycle (EGR) sampling system. The design of the sampling train allows the operator to maintain a constant flow rate through an inertial sampler while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. This manual specifically addresses the operation of the EGR system for determination of stationary source PM-10 emissions. Material in the text includes: construction details, calibration procedures, presampling calculations, sample retrieval, data reduction, and equipment maintenance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT
Release to Public

19. SECURITY CLASS *(This Report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLE

PB89-189856

EPA/600/3-88/058
April 1989

APPLICATION GUIDE FOR THE SOURCE PM_{10} EXHAUST GAS RECYCLE SAMPLING SYSTEM

by

Randal S. Martin
Sherry S. Dawes
Ashley D. Williamson
William E. Farthing
Southern Research Institute
Birmingham, AL 35255-5305

Contract No. 68-02-4442

Project Officer

Thomas E. Ward
Quality Assurance Division
Atmospheric Research and Exposure Assessment Laboratory
Research Triangle Park, North Carolina 27711

ATMOSPHERIC RESEARCH AND EXPOSURE ASSESSMENT LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

DISCLAIMER AND PEER REVIEW NOTICE

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under contract 68-02-4442 to Southern Research Institute. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Measurement and monitoring research efforts are designed to anticipate environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems for air, implementation of agency-wide quality assurance programs for air pollution measurement systems, and supplying technical support to other groups in the Agency including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

The environmental effects of PM_{10} particulate matter are of concern to the Agency. Acceptable measurement methodology is critical for proper assessment of the impact on the environment of these emissions from stationary sources. Preparation of a manual which specifies measurement procedures is a key component for assuring reliable test data. This manual was prepared to describe the construction, maintenance, and operating procedures for the Exhaust Gas Recycle approach for measurement of PM_{10} emissions from stationary sources.

Gary J. Foley
Acting Director
Atmospheric Research and Exposure Assessment Laboratory
Research Triangle Park, North Carolina 27711

ABSTRACT

This report describes assembly, operation, and maintenance of the Exhaust Gas Recycle (EGR) sampling train. Although the potential uses of this system are numerous, this manual specifically addresses the operation of the EGR train for the determination of stationary source PM_{10} emissions. The design of the EGR system allows the operator to maintain a preselected constant flow rate through an inertial sampler while the gas flow rate into the sampling nozzle is adjusted at each traverse point to remain isokinetic with the local gas velocity. The isokinetic sample flow rate, Q_s, enters the sample nozzle where it is mixed with a metered flow rate of recycled exhaust gas, Q_r. The combination of these two flow rates brings the total flow rate to the predetermined constant level, Q_t. After passing through the inertial sampler, which collects the larger particle size fraction (>10 μm), through an in-stack filter which collects the smaller PM_{10} size fraction, and through a heated probe, the water vapor is removed from the gas stream by condensation in an ice-cooled condenser or impinger train. The gas stream then enters the control console where the total flow rate is eventually split into the component flow rates, Q_s and Q_r. The sample flow rate is monitored in the usual manner by using a dry gas meter and calibrated orifice. The total and recycle flow rates are measured by calibrated laminar flow elements (LFEs). The inertial sizing device described in this document is Cyclone I of the Southern Research Institute (SRI)/EPA five-stage series cyclone sampler followed by an in-stack filter. Laboratory evaluation of this device has shown Cyclone I produces a 10-μm size cut at a flow rate of approximately 0.5 dscfm; the precise flow rate depends on stack conditions. Calibration procedures for the EGR sampling train are essentially the same as standard Method 5 or Method 17 trains with the exception of the two LFEs. Calibration of the total flow rate LFE may be performed simultaneously with the dry gas meter and orifice.

Calibration of the recycle flow rate LFE requires an additional, separate step. Pretest calculation of sampling parameters for operation of the system involves determining target pressure differentials (ΔH, ΔP_t, and ΔP_r) for a range of possible velocity pressures, ΔP_{vel}, and stack temperatures. An approximate solution of the governing equations provides acceptable agreement with the exact solution and allows calculation of these parameters in a few simple steps. Operation of the sampling train is the same as Method 5 except that valve settings must be adjusted for two flow rates (Q_t and Q_s) rather than one (Q_s). Sample retrieval is dependent on the type of sampling device used. For Cyclone I, a combination of brushing and rinsing with a suitable solvent is required to quantitatively recover the larger size fraction. The PM_{10} size fraction is recovered by simply removing the filter from the filter holder. Test data analysis requires essentially the same calculations as outlined in Method 5 with the addition of the cyclone cut size, or D_{50}. Other postsampling activities include calibration checks and equipment maintenance.

CONTENTS

Page

Forward iii

Abstract iv

Figures x

Tables xii

Symbols xiii

Acknowledgement xvi

1. Introduction 1
2. Construction 3
   - 2.1. General system description 3
   - 2.2. Component detail 5
     - 2.2.1. Control unit 13
     - 2.2.2. Condenser/Impinger train 17
     - 2.2.3. Umbilical 18
     - 2.2.4. Sampling/Reheat probe 18
     - 2.2.5. Exhaust gas recycle nozzle 20
     - 2.2.6. PM_{10} sampler 22
3. Calibration 32
   - 3.1. Flow metering system 32
   - 3.2. Pitot tube 36
   - 3.3. EGR nozzles 37
   - 3.4. Thermocouples 38
   - 3.5. Magnehelic gauges 38
   - 3.6. Support equipment 38
4. Presampling Activities 39
   - 4.1. Equipment calibration and checks 39
   - 4.2. Preparation of sampling reagents 41

CONTENTS (Continued)

Page

5. Sampling Parameters 42
    5.1. Preliminary measurements 42
    5.2. EGR flow rates 44
    5.3. Target pressure differentials (ΔH, ΔP_t, ΔP_r) 45
    5.4. Nozzle selection 55
6. Taking the Sample 56
    6.1. Field assembly 56
    6.2. Leak test 57
    6.3. Pretest equipment warm-up 58
    6.4. Flow rates 59
    6.5. Traversing 60
    6.6. Flow rate checks 60
    6.7. Shutdown orientation 60
    6.8. Data logging 61
7. Sample Retrieval 63
    7.1. Recovery of particulate mass 63
    7.2. Moisture determination 64
8. Postsampling Checks 65
    8.1. Equipment calibration checks 65
    8.2. Sample analysis 66
9. Data Analysis 68
    9.1. Average run parameters 68
    9.2. Dry gas (sample) volume 68
    9.3. Sample flow rate 69
    9.4. Recycle and total gas flow rates 69
    9.5. Volume of water vapor 70
    9.6. Moisture content 70
    9.7. Flow rates (actual conditions) 71
    9.8. Recycle ratio 71
    9.9. Stack gas velocity 71
    9.10. Concentration 72

CONTENTS (Continued)

Page

9.11. Sampler D_{50} 72
9.12. Percent isokinetic 74
10. Maintenance 75
10.1. Vacuum system 75
10.2. EGR pump 75
10.3. Magnehelic differential pressure gauges 77
10.3.1. Zero adjustment 77
10.3.2. Calibration check 77
10.3.3. Recalibration 78
10.4. Dual manometer 79
10.5. Pitot tube 80
10.6. Nozzles 80
10.7. Thermocouples 81
10.8. EGR sampling probe 81
10.8.1. Probe cleaning 81
10.8.2. Probe heater check 82
10.9. Condensing system 82
11. Auditing Procedures 84
12. Recommended Standards for Establishing Traceability 86

References 87

Appendices

A. EGR System Components List 89
B. EGR System Shop Drawings 99
C. Blank Data Forms 110
D. HP41C Setup Program 129

Glossary 134

FIGURES

Page

1. Gas Flow in EGR Train 3

2. Schematic of the EGR Train 4

3. EGR sampling system control module (front view) 6

4. EGR sampling system control module (rear view) 7

5. EGR sampling system control module (rear view) showing internal components 8

6. EGR sampling system control module (right side) 9

7. EGR sampling system control module (left side) with 4-cfm Pump 10

8. EGR PM_{10} cyclone sampling device (front view) 11

9. EGR PM_{10} cyclone sampling device (side view) 12

10. EGR concept nozzle assembly 21

11. Calibration system for heated aerosols 24

12. Efficiency envelope for PM_{10} sampler 30

13. Cyclone I Dimensions 31

14. EGR Setup Calculation Worksheet I: Orifice ΔH 50

15. EGR Setup Calculation Worksheet II: Total Flow LFE ΔP 51

16. EGR Setup Calculation Worksheet III: Recycle Flow LFE ΔP 53

17. Suggested EGR Run sheet 62

B-1. EGR Panel (Control Box) 96

B-2. EGR Sampling System, (Manometer Leveling Accessories) 97

FIGURES (Continued)

Page

B-3. EGR Sampling System, DGM Supports 98

B-4. EGR Sampling System, Back Panel: Magnehelic Zero Valves........... 99

B-5. EGR Sampling System, Probe Components 100

B-6. EGR Sampling System, Sample Orifice Assembly 101

B-7. EGR Sampling System, EGR Nozzle Assembly 102

B-8. EGR Sampling System, Pitot Assembly 103

B-9. EGR Sampling System, EGR Circuit Diagram 104

B-10. EGR Sampling Train, Condenser 105

TABLES

Page

1. Performance Specifications for Source PM_{10} Samplers 28

2. Particle Sizes and Nominal Gas Velocities for Efficiency Performance Tests 29

SYMBOLS

A_n	Cross-sectional area of sampling nozzle, ft^2
B_{mix}	Proportion by volume of water vapor in mixed gas, dimensionless
B_{ws}	Water fraction of stack gas (also f_{H_2O})
C_m	Concentration of particulate, mg/dNm^3
C'_m	Concentration of particulate matter, gr/dscf
C_p	Pitot tube coefficient
D_{50}	Cyclone cut diameter, µm
d_n	Diameter of nozzle n, in.
$D_{P_{stack}}$	Stack differential pressure, in. H_2O
f_c	Fraction CO_2
f_o	Fraction O_2
f_{H_2O}	Water fraction of stack gas (also B_{ws})
I	Percent isokinetic sampling
K_p	85.48 ft/s (lb/mole-°R)
M_d	Dry molecular weight of stack gas, lb/mole
M_p	Mass of collected particulate (either per stage or total), mg
M_w	Wet molecular weight of stack gas, lb/mole
M_{wm}	Wet molecular weight of the mixed gas, lb/mole
M_{H_2O}	Molecular weight of water, 18 lb/mole
P_a	Ambient pressure, in. Hg
P_L	Absolute pressure at LFE inlet, in. Hg
P_s	Absolute stack pressure, in. Hg
P_{ST}	Absolute pressure at standard conditions, 29.92 in. Hg
PR	Recycle ratio at stack conditions, percent
Q_d	The sampler flow rate when the total flow is composed entirely of dry recycle gas (100% recycle)
Q_s	Flow rate through the sampler (sampler conditions), acfm

$Q_{s_{ST}}$	Sample flow rate (standard conditions), ft^3/min
Q_t	Total (mixed) cyclone flow rate (sampler conditions), acfm
$Q_{t_{ST}}$	Total flowrate through the sampler (standard conditions, dry basis), dscfm
Q_r	Recycle flow rate, acfm
Q_w	The sampler flow rate when the total flow is composed entirely of sample gas with a known moisture fraction (0% recycle)
R_u	Ideal gas constant, 21.83 in. Hg-ft^3/mole-°R
S_r	Recycle flow LFE calibration constant
S_t	Total flow LFE calibration constant
T_M	Absolute gas meter temperature, °R
T_L	LFE temperature, °R
T_s	Absolute stack gas temperature, °R
T_{ST}	Absolute temperature at standard conditions, 528 °R
v_{avg}	Average stack velocity, ft/s
$V_{\ell c}$	Total volume of liquid collected in impingers or condenser/silica gel, mL
V_M	Volume of gas sample flow through the dry gas meter (meter conditions), ft^3
V_{MS}	Volume of gas sample flow through the dry gas meter (standard conditions), ft^3
V_{max}	Maximum expected stack gas velocity, ft/s
V_s	Stack gas velocity, ft/s
V_{WS}	Volume of water vapor in the gas sample (standard conditions), ft^3
W_r	Recycle flow LFE calibration constant
W_t	Total flow LFE calibration constant
ΔH	Orifice pressure drop
$\Delta H_@$	Orifice pressure differential for a flow rate of 0.75 cfm at standard conditions, in. H_2O
ΔP_{EGR}	Velocity pressure drop of EGR S-type pitot tube, in. H_2O
ΔP_r	Pressure drop across the recycle flow LFE, in. H_2O
ΔP_{ST}	Velocity pressure drop of standard pitot tube, in. H_2O
ΔP_t	Pressure drp across the recycle flow LFE, in. H_2O
ΔP_{vel}	Velocity pressure head, in. H_2O

ρ_{H_2O}	Density of water, 1 g/mL
θ	Total run time, min
μ	Gas viscosity, μp
μ_d	Stack gas viscosity at 0% moisture
μ_L	Gas viscosity at LFE conditions
μ_m	Viscosity of the mixed gas, μp
μ_{ST}	Gas viscosity at standard conditions, 180.1 μp
μ_w	Stack gas viscosity for a known moisture fraction
$(\sqrt{\Delta P_{vel}})_{avg}$	Average square root of velocity ΔPs, used to calculate average stack velocity.
γ	Gas meter calibration constant

ACKNOWLEDGEMENT

This manual builds on material presented in two previous reports written on the subject: "Operations Manual for Exhaust Gas Recirculation (EGR) Sampling Train," prepared for the Atmospheric Research and Exposure Assessment Laboratory of EPA, Contract No. 68-02-3118, August 1984, and an expanded version of that manual, "Procedures Manual for The Recommended ARB Size Specific Stationary Source Particulate Method (Emission Gas Recycle)," prepared for the California Air Resources Board, Contract No. A3-092-32, May 1986.

SECTION 1

INTRODUCTION

To ensure a representative sample of particulate matter is obtained from a flowing gas stream, the sample must be withdrawn isokinetically; that is, the gas flow rate of the sample must be adjusted so that the velocity in the sampling nozzle equals that in the surrounding gas stream. If a velocity mismatch occurs at the nozzle, the particulate matter in the sample gas may be selectively enriched or depleted; the concentration increase or decrease will depend in part on the particle size. This bias is avoided in EPA Reference Methods 5 and 17 by specifying isokinetic sampling. To obtain a spatially representative sample, the duct is divided into a number of equal area zones. The centroid of each zone is then sampled for a fixed time interval, and the sample flow rate is adjusted at each centroid to be isokinetic with respect to the local gas stream velocity.

The procedure outlined above is satisfactory for total particulate mass measurements. However, when sampling is conducted with inertial particle-sizing devices such as cascade impactors or sampling cyclones, an additional constraint is introduced. These samplers must be operated at a constant flow rate to maintain constant size cuts for each particle size fraction. For a fixed nozzle size, it is impossible to satisfy both the requirements of constant sampler flow rate and isokinetic nozzle velocity with conventional sampling trains.

This manual describes assembly, operation, and maintenance of a sampling train that allows isokinetic sampling while maintaining a constant flow rate through an inertial particle-sizing device. The sampling train uses the principle of exhaust gas recycle (EGR). Its design allows a preselected constant flow rate through the inertial sampler while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. This method may be identified in other EPA documents as the Emission Gas Recycle method. Although the potential uses of this system are numerous, this manual specifically addresses the operation of the EGR system for the determination of stationary source emissions of particulate matter with diameter ≤ 10 µm (PM_{10}). The sizing device described consists of a commercially available version of Cyclone I of the Southern Research Institute (SRI)/EPA five-stage series cyclone sampler (Smith et al. 1979) and an in-stack backup filter. However, most components of the EGR system are independent of the type of inertial sampler used, and the material provided in this manual pertaining to these components is applicable to most sampling situations.

This manual is organized chronologically, from construction details to postsampling and audit checks of the system. Section 2 describes the critical construction details of the EGR system. Section 3 describes the procedures by which various components of the system may be calibrated. Activities that are required or recommended before field use of the system are outlined in Section 4. Section 5 describes the calculations required to obtain the system sampling parameters before sampling, and Section 6 outlines the steps to follow during operation of the sampling system. Retrieval of the collected sample is described in Section 7. Sections 8 and 9 describe postsampling checks of the system and analysis of the field data. Routine maintenance of the EGR sampling system is discussed in Section 10. Auditing procedures and recommended standards are described in Sections 11 and 12. Included as Appendix A is a list of components necessary to fabricate an EGR system similar to that developed at SRI. Appendix B contains a complete set of fabrication drawings for the prototype EGR system. Examples of data forms necessary in the course of calibrating and operating the EGR system can be found in Appendix C. Appendix D contains a listing of a program written for the HP41C that performs EGR setup calculations.

SECTION 2

CONSTRUCTION

2.1. GENERAL SYSTEM DESCRIPTION

The principle of operation of the EGR train is illustrated in Figure 1. Stack gas is extracted isokinetically at volumetric flow rate Q_s. If the stack moisture fraction is f_{H_2O}, the sample flow consists of $Q_s(f_{H_2O})$ moisture and $Q_s(1 - f_{H_2O})$ dry gas. In the EGR nozzle a flow, Q_r, of dry recycle gas is added to the sample stream to bring the total flow rate to the predetermined constant level, Q_t. In the impingers or condenser, the moisture content $Q_s(f_{H_2O})$ is removed. Downstream of the pump and total flow metering element, the recycle flow (Q_r) is diverted by means of an adjustable valve. By mass balance, in a leak-free system, the remaining flow that passes through the dry gas meter (DGM) and orifice will simply be $Q_s(1 - f_{H_2O})$, exactly as would occur in an isokinetic sampling train without exhaust gas recycle (Martin, 1971).

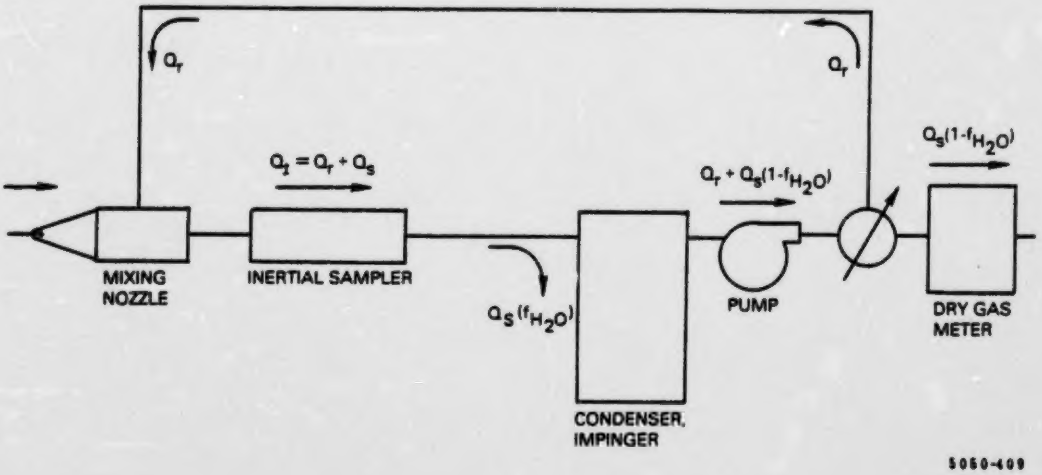

Q_r
Q_r
$Q_s(1-f_{H_2O})$
Q_s
$Q_t = Q_r + Q_s$
$Q_r + Q_s(1-f_{H_2O})$
MIXING NOZZLE
INERTIAL SAMPLER
$Q_s(f_{H_2O})$
PUMP
DRY GAS METER
CONDENSER, IMPINGER
5060-409

Figure 1. Gas flow in EGR train (Harris and Beddingfield, 1981).

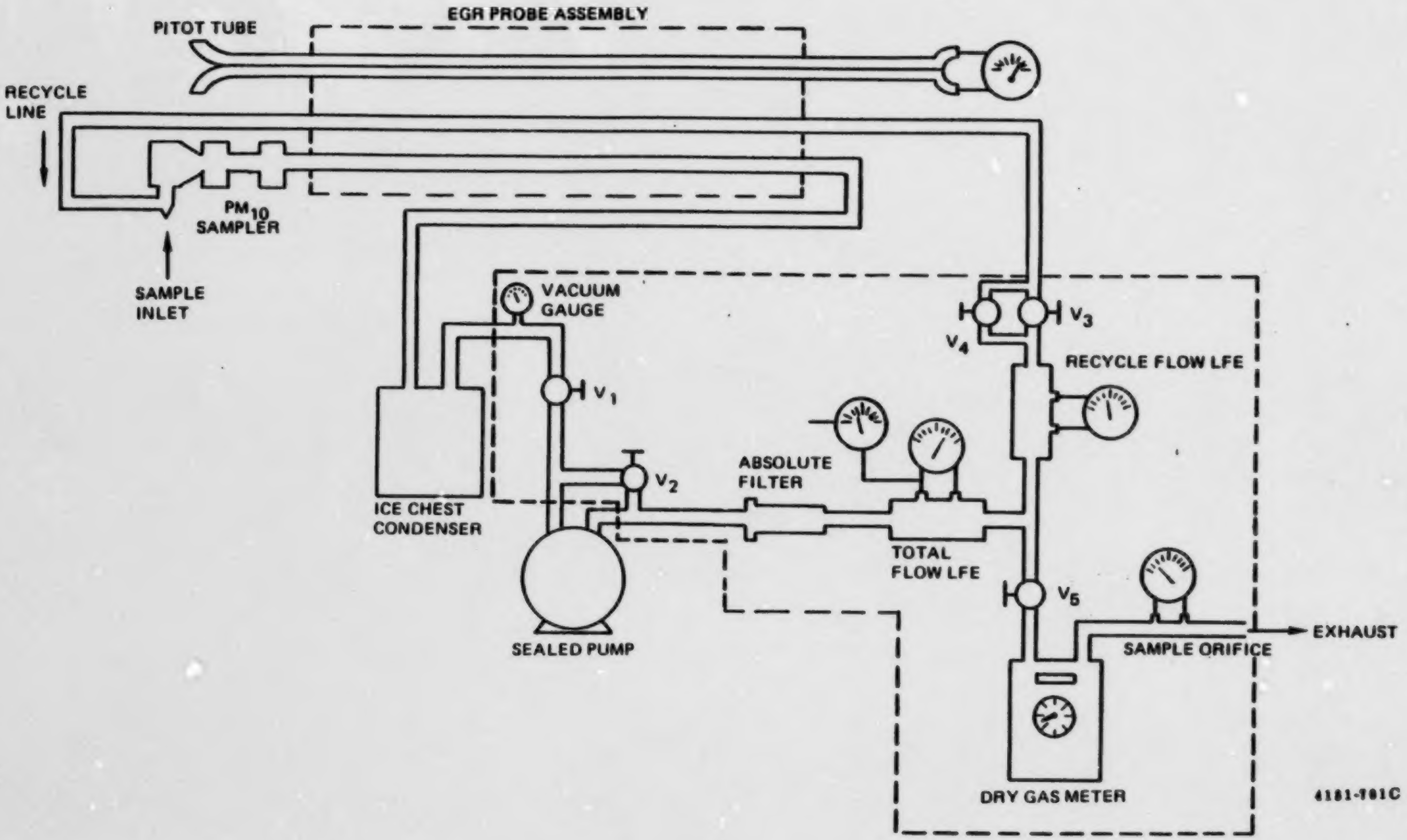

EGR PROBE ASSEMBLY
PITOT TUBE
RECYCLE LINE
PM$_{10}$ SAMPLER
SAMPLE INLET
VACUUM GAUGE
V_1
V_2
V_3
V_4
V_5
RECYCLE FLOW LFE
ABSOLUTE FILTER
ICE CHEST CONDENSER
TOTAL FLOW LFE
SEALED PUMP
EXHAUST
SAMPLE ORIFICE
DRY GAS METER
4181-701C

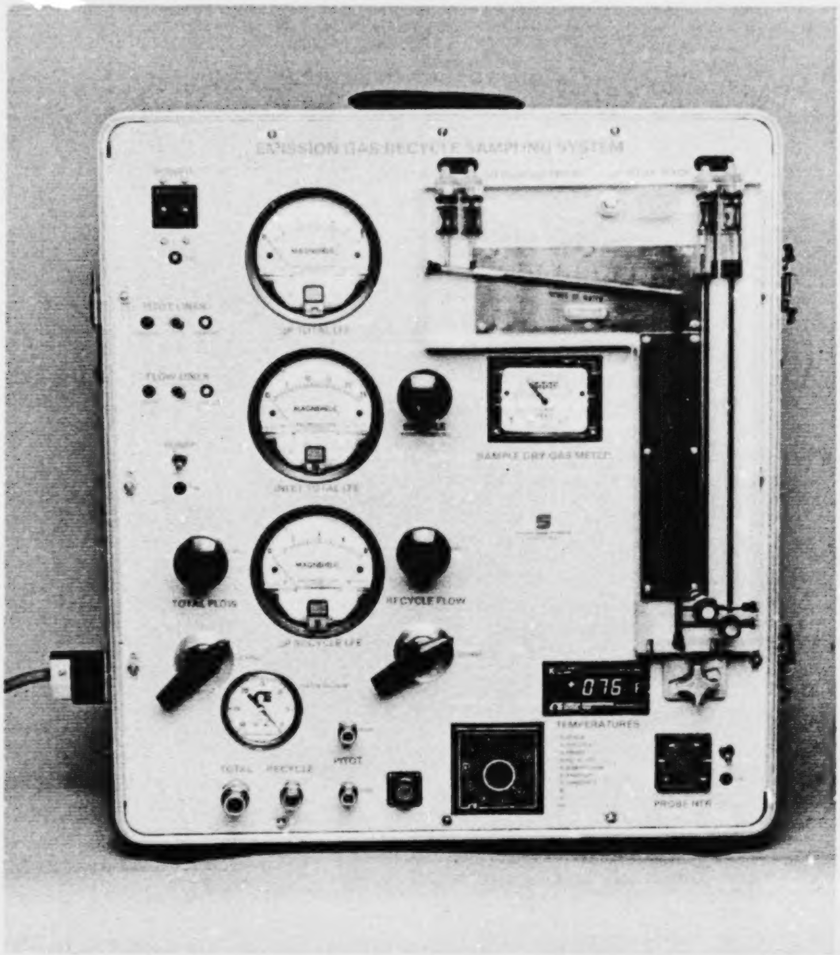
Figure 2. Schematic of the EGR train (Williamson et al., 1984).

A block diagram of the research train of Williamson et al. (1984) is shown in Figure 2. The gas sample containing particulate matter enters through the sample inlet of the mixing nozzle. After passing through the PM_{10} classifier, which collects the larger particle size fraction (>10 μm), through a second stage, which collects the smaller PM_{10} size fraction, and through a heated probe, the combined sample and recycle gas passes through an ice-cooled condenser or impinger train, followed by a sealed pump controlled by valves V_1 and V_2 for coarse and fine flow adjustment, respectively. From this point the gas in a standard isokinetic sampling train would pass directly to the DGM and sample orifice and finally be exhausted. In the train as modified for EGR, after the gas exits the pump, it passes through an absolute filter and the first of two laminar flow elements (LFEs), where the total flow is measured. The gas stream is then split into the recycle and sample lines. The recycle gas flow is controlled by valves V_3 and V_4 and is measured by a second LFE. The sample flow is monitored in the usual manner by using a DGM and a calibrated orifice. Valve V_5, at the inlet to the DGM, was added to the system to extend the range of control to higher recycle percentages by adding back-pressure to the sample flow line.

Figures 3 through 7 show the control module for the SRI/EPA second-generation EGR system. As can be seen, the module appears similar to a Method 5 sampling box, with the exception of the total, inlet, and recycle magnehelic gauges, the recycle and sample (back-pressure) control valves, and the recycle gas outlet. The probe head is shown in Figures 8 and 9 with a filter in line behind the SRI/EPA Cyclone I for collecting the PM_{10} size fraction. The location of the pitot tube relative to the cyclone body shown in the figures was used during initial testing of the method. The location of the pitot tube was eventually changed to that described in Section 3.2.

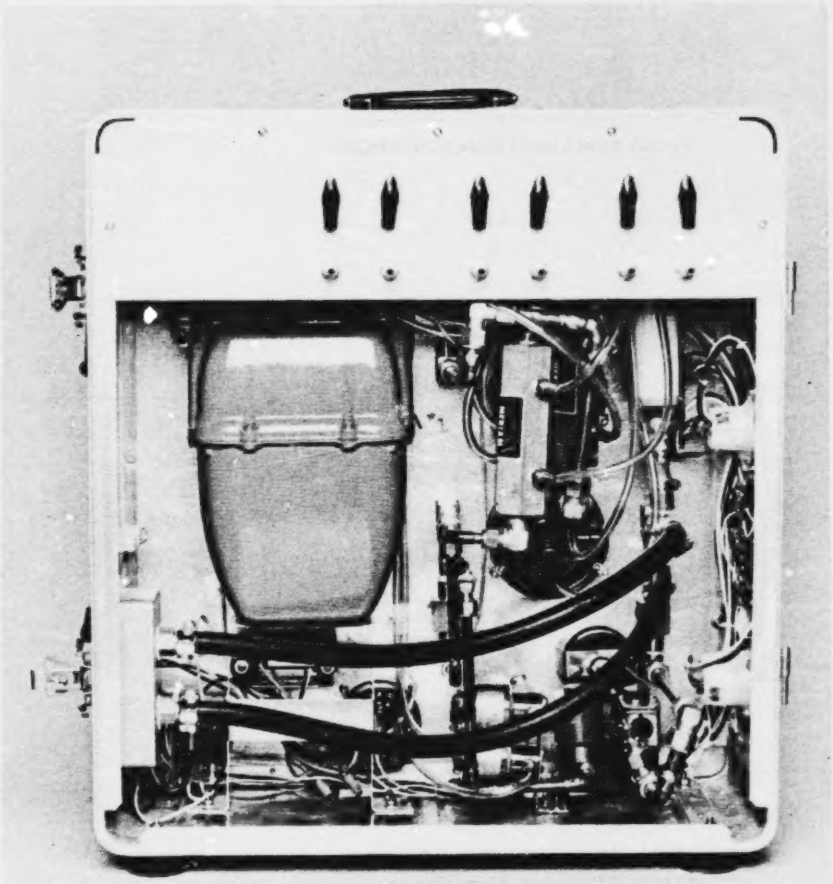
2.2. COMPONENT DETAIL

This section describes essential and specific components of the SRI/EPA exhaust gas recycle train. The included specifications are intended as a general outline. Substitutions of the designated components may be acceptable if


EMISSION GAS RECYCLE SAMPLING SYSTEM
FLOW LINES
TOTAL FLOW
RECYCLE FLOW
SAMPLE DRY GAS METER
076
TEMPERATURES
PITOT
TOTAL
RECYCLE
PROBE HTR

5598-30

Figure 3. EGR sampling system control module (front view).



5598-31

Figure 4. EGR sampling system control module (rear view).

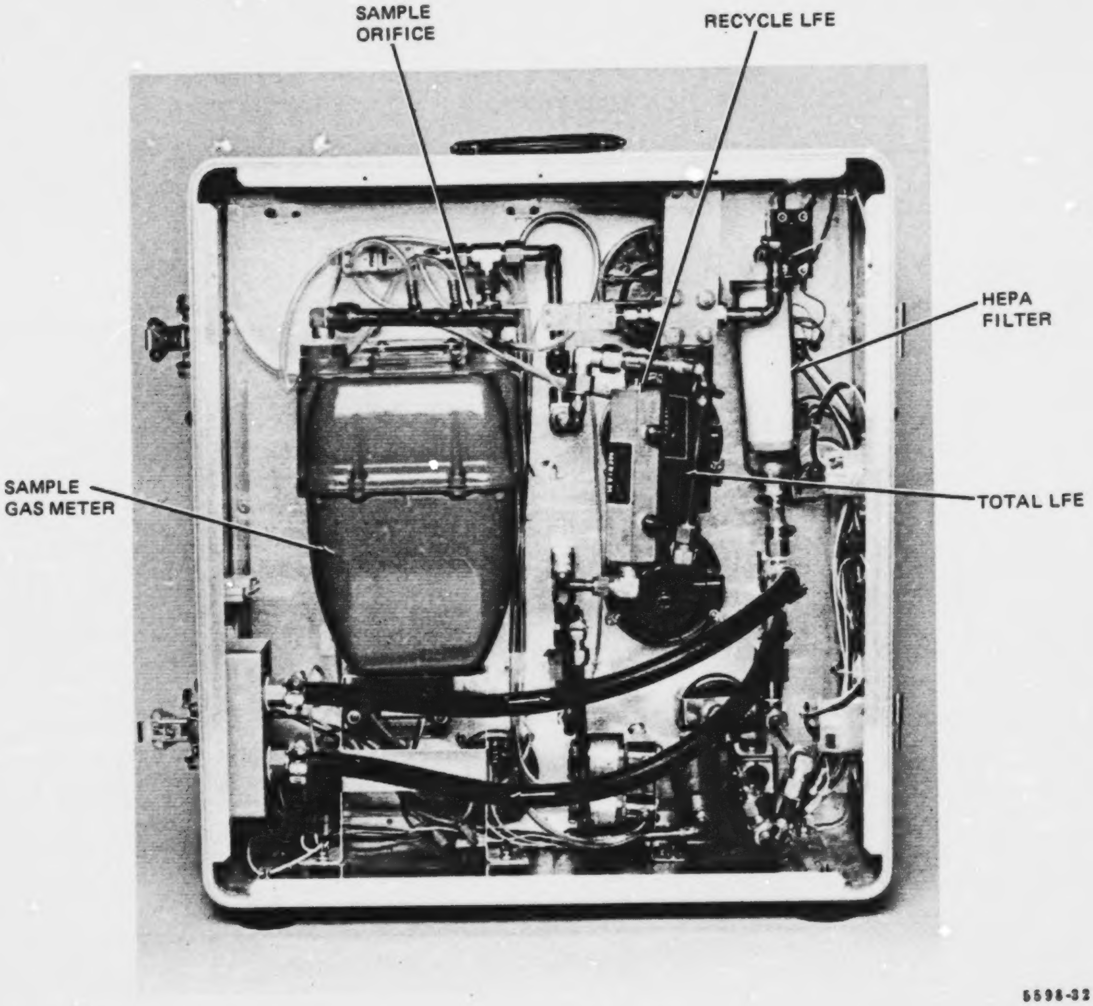

SAMPLE ORIFICE
RECYCLE LFE
HEPA FILTER
SAMPLE GAS METER
TOTAL LFE
5598-32

Figure 5. EGR sampling system control module (rear view) showing internal components.

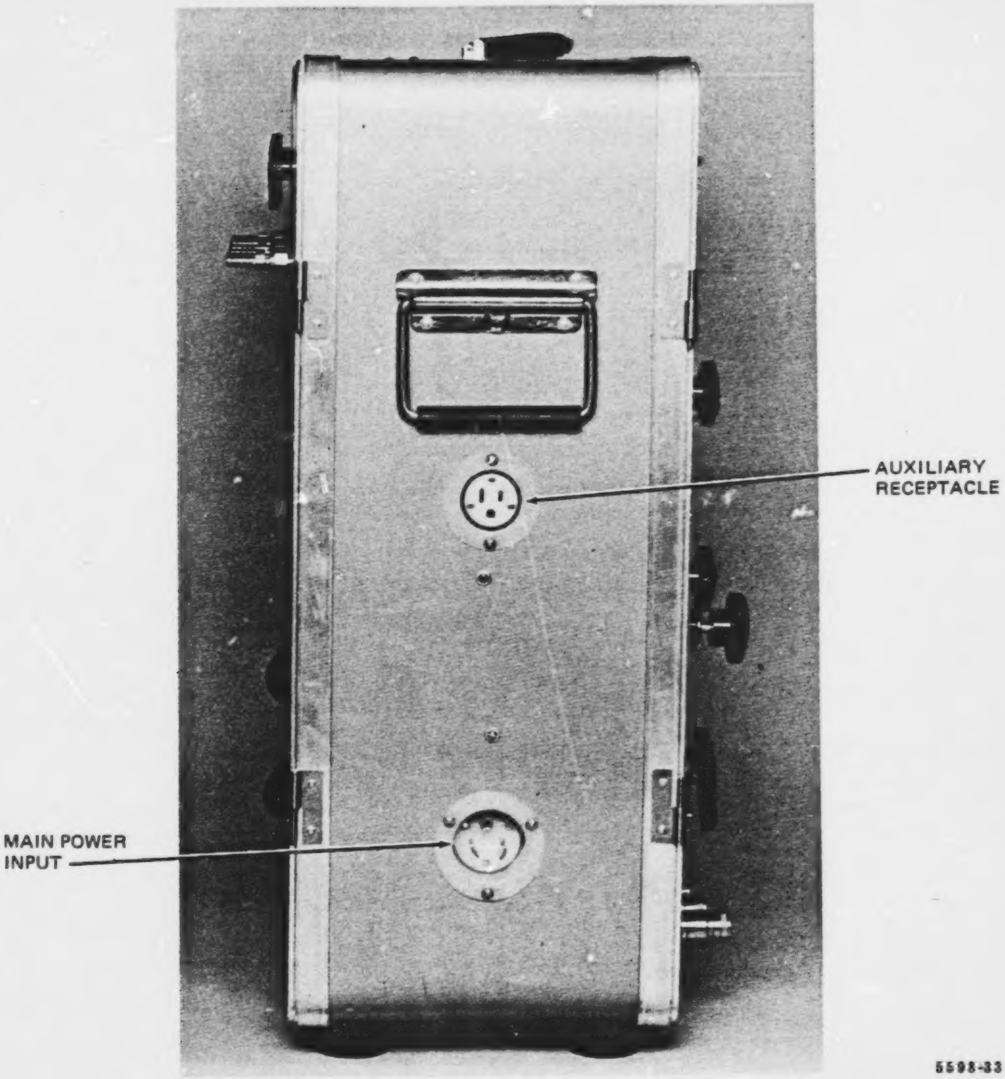
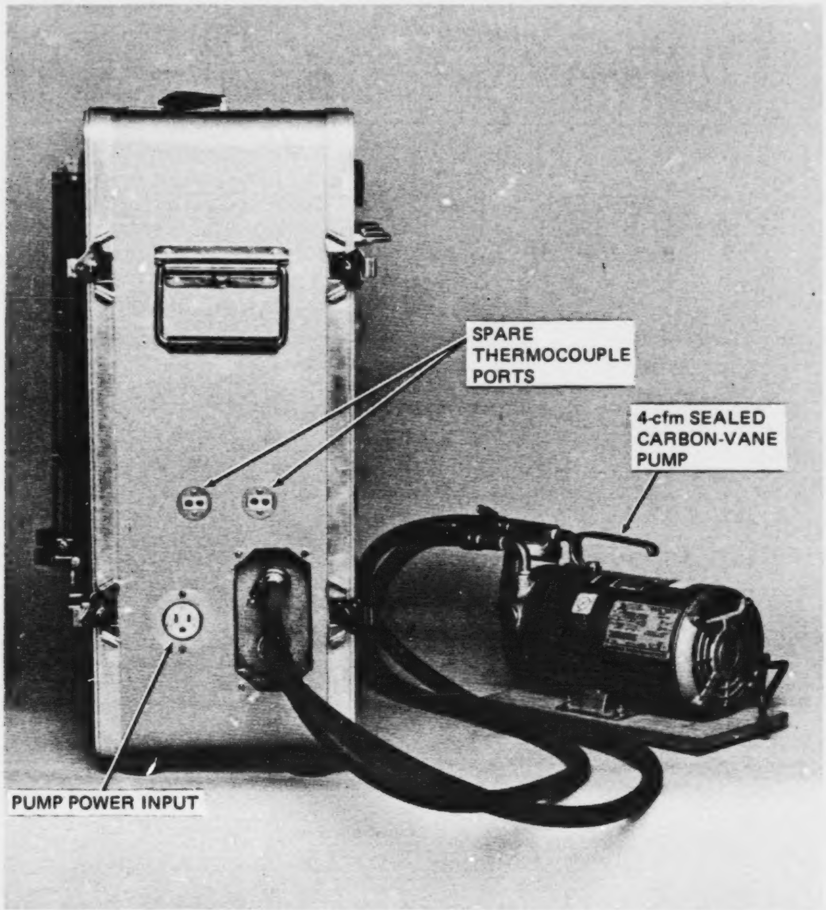
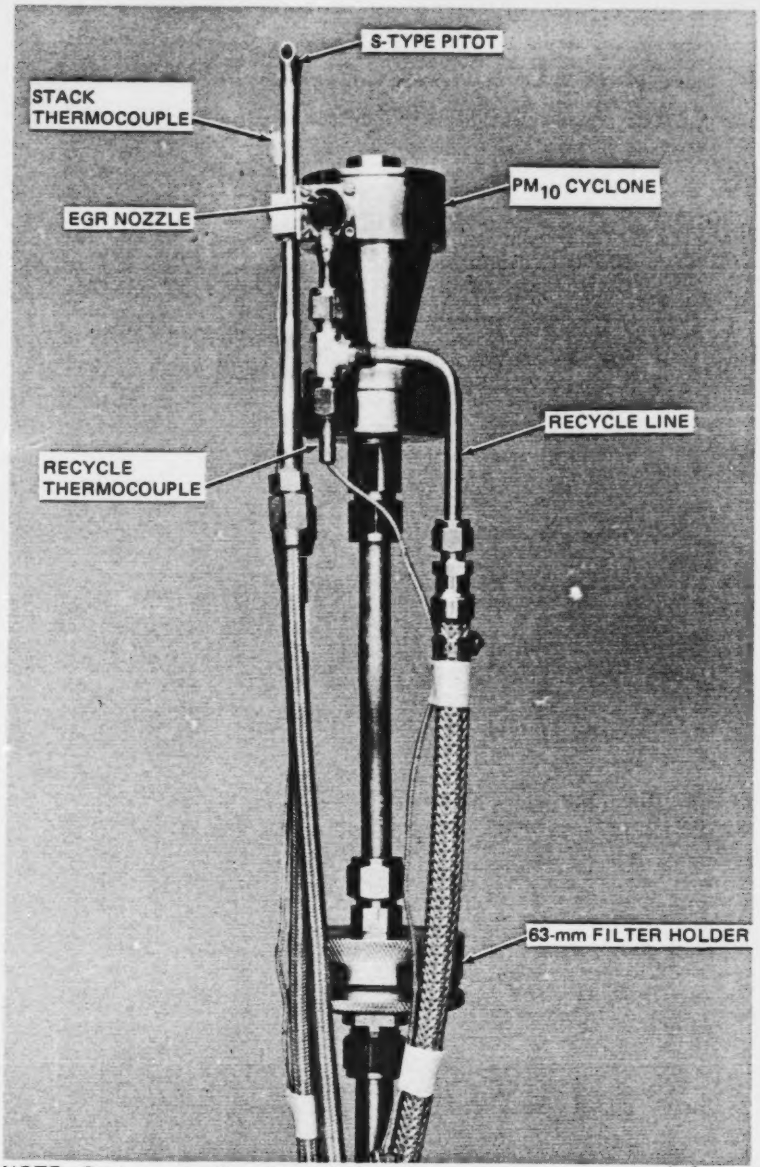

AUXILIARY RECEPTACLE
MAIN POWER INPUT
5598-33

Figure 6. EGR sampling system control module (right side).


SPARE THERMOCOUPLE PORTS
4-cfm SEALED CARBON-VANE PUMP
PUMP POWER INPUT

5598-34

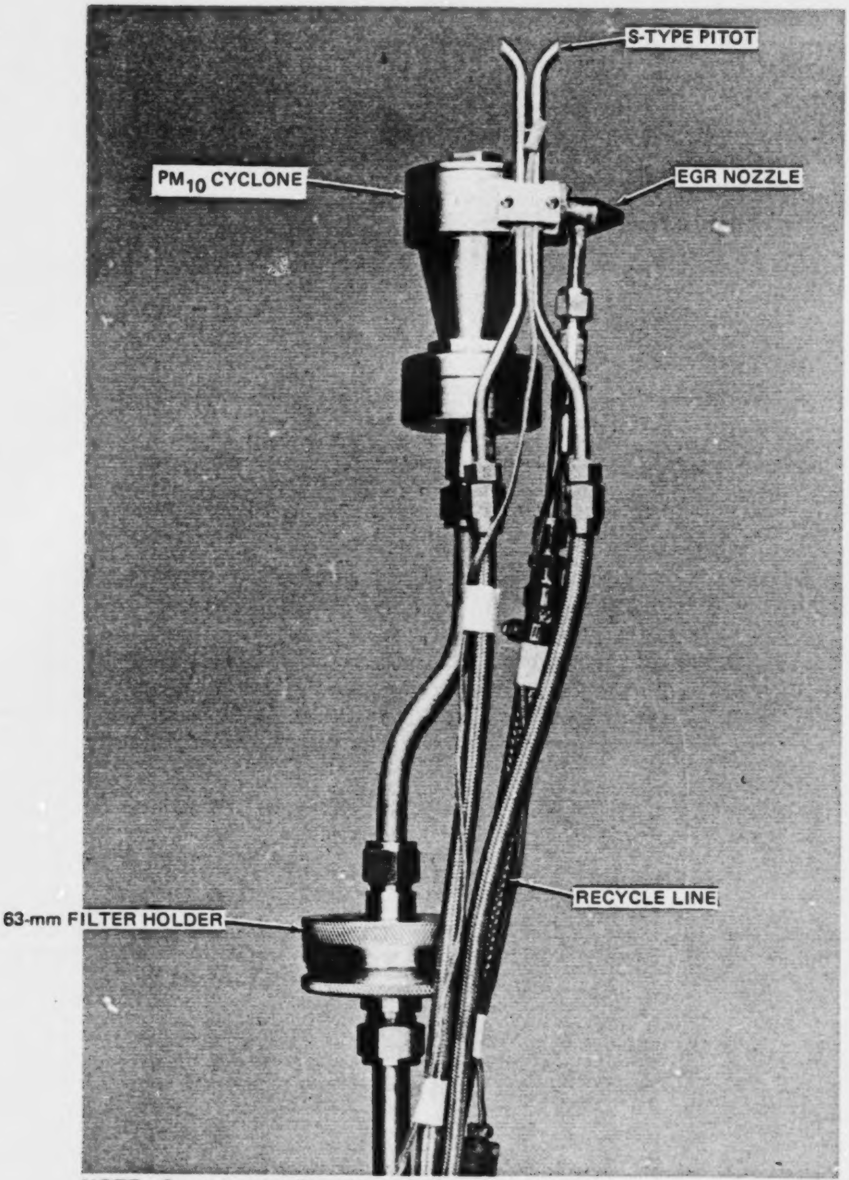
Figure 7. EGR sampling system control module (left side) with 4-cfm pump.


S-TYPE PITOT
STACK THERMOCOUPLE
PM_{10} CYCLONE
EGR NOZZLE
RECYCLE LINE
RECYCLE THERMOCOUPLE
63-mm FILTER HOLDER

NOTE: See text regarding pitot tube location.

5598-35

Figure 8. EGR PM_{10} cyclone sampling device (front view).


S-TYPE PITOT
PM_{10} CYCLONE
EGR NOZZLE
RECYCLE LINE
63-mm FILTER HOLDER

NOTE: See text regarding pitot tube location.

5598-86

Figure 9. EGR PM_{10} cyclone sampling device (side view).

it can be shown that the substitutions do not negatively affect the principles of exhaust gas recycle. An itemized list of all components used for construction of the EGR sampling system can be found in Appendix A. Additionally, a complete set of shop drawings, as used by SRI for fabricating the EGR system, can be found in Appendix B.

2.2.1. Control Unit

The EGR control unit actually consists of two units, the control box and a leak-free pump. In many source sampling systems, the pump is internal to the control box. However, the combined weight of the EGR control box and the 4-cfm pump is approximately 115 lb. Therefore, to distribute the system weight and minimize the control box dimensions, the EGR pump is external to the system. The pump is connected to the control box via 1/2-in. i.d. flexible, high-pressure rubber hose. Full-flow, quick-connect fittings allow rapid assembly and disassembly.

The gas recirculated within the EGR system must be free of any foreign particles or vapors; therefore, a leak-free, carbon-vane 4-cfm pump (Andersen Samplers, Inc., #991584) is used with the EGR system. The pump operates on 115 V ac and draws approximately 4-6 A. The specified pump requires no lubrication, and little maintenance is needed to ensure long working life. It is suggested the pump be housed, at least during transportation and storage, in a separate and unique container (e.g., a tool box). The pump may be left in the housing during system operation; however, caution should be exercised to protect the pump against overheating. A small circulating fan installed in the pump box and ventilated to the outside should be adequate.

The control box contains the required electrical circuits, internal plumbing, flow control valves, devices to monitor flow and pressure, and temperature readout and control instrumentation. The components are housed in a custom-sized, heavy-duty transit case (Gemini, Inc., #GH2325RPF-2). The electricity to the system (115 V ac at 15 A) is brought into the control box via a single length of 12-gauge, three-wire cable. To prevent accidental disconnection during sampling runs, the electrical input cable is attached to the control box with a locking plug and receptacle. The input power is paralleled to the various pieces of electrical equipment (solenoid valves, indicator lights, pump, temperature readout, and heater tape control) via standard, double-row terminal strips.

The internal plumbing of the EGR sampling train can be inferred from the schematic drawing shown in Figure 2 and is shown in some detail in Figures 4 and 5. Rigid copper tubing, 1/2-in. o.d. for the total flow and sample lines and 3/8-in. o.d. for the recycle line, is used for all internal flow lines. The lines are assembled into the required geometry by using a combination of copper "sweat" fittings and a variety of brass compression tube fittings. The total flow (mixed gas) enters the control box just upstream of the system vacuum gauge, through a 1/2-in. bulkhead quick-connect fitting. As previously mentioned, this flow is controlled through the pump by valves V_1 (coarse adjust) and V_2 (fine adjust). After exiting the pump, the total flow is directed through an absolute, HEPA-type, capsule filter (Gelman Sciences #12127). The filter prevents artifact particulate matter (e.g., graphite dust from the pump vanes) from plugging the flow-monitoring devices or entering the recycle gas stream. The particle-free total flow is monitored by an appropriately sized LFE, after which the flow is split into the recycle and sample flows. The recycle flow is also monitored with an appropriately sized LFE and controlled with a set of coarse and fine adjust valves (V_3 and V_4, respectively). The recycle gas then exits the control box through a 3/8-in. bulkhead quick-connect fitting. A normally open, 0.281-in. orifice, two-way solenoid valve (Automatic Switch Co., #8262A152) is located at both the total flow inlet and the recycle outlet. The solenoid valves may be switched closed while the sampler is in-stack and is not sampling; this prevents erroneous sample gas meter volumes and helps protect the sampling filter from rupture due to excess duct pressures. The sample flow, after the split from the total flow, is monitored in a manner similar to that of a standard Method 5 train by using a DGM and a calibrated orifice. The back-pressure valve (V_5) added to the sample line is similar to the fine adjustment valves used in the recycle and total flow lines. The fine adjust valves are 1/4-in. orifice, stainless steel, angled regulating valves (Whitey #SS-1RF4-A). The coarse valves are stainless steel ball valves with a 0.281-in. orifice (Whitey #SS-44F4).

2.2.1.1. Flow Metering Devices--

As mentioned above, the total and recycle flows are monitored by using LFEs. These are differential-pressure flow measurement devices composed of a stainless steel capillary matrix. The calibration curve of most LFEs approaches linearity over a wide flow range, and accuracy is limited mainly by flow stability and pressure gauge readability. Pressure drop (ΔP) across an LFE is a function of the friction between the flowing air and the walls of the LFE's capillary section. Because the pressure differential is not produced by a restriction, such as an orifice, the absolute system pressure does not contribute to the ΔP-flow rate relationship of an LFE (at meter conditions). The total flow LFE should have a rated capacity of at least 1.0 cfm without excessive ΔP (Meriam Instrument #50MJ10-1/2 type 10). The LFE used to monitor the recycle flow rate should have a minimum capacity of 0.7 cfm (Meriam Instrument #50MJ10-1/2 type 11). During construction, care should be taken to prevent dust and debris from entering the LFE's capillary section. Any accumulation of foreign matter within the laminar matrix could seriously affect the accuracy and reliability of the device. Periodically, the capsule filter immediately upstream of the total flow LFE should be inspected for filter integrity, efficiency, and pressure differential. If the HEPA filter were to rupture, particulate matter from the pump could enter the LFEs, altering the known calibration and potentially altering the LFEs' linearity.

The sample gas is measured and monitored by using an orifice-DGM assembly similar to that of a Method 5 train. The DGM should have a flow rate capacity of at least 1.0 cfm and be readable to 0.002 ft^3 (Rockwell Series T-100). The geometry of the sample gas orifice, which connects directly to the outlet of the DGM, is comparable to that of the Method 5 sample orifice. However, because of the reduced total flow rate of the PM_{10} sampler (approximately 0.45 scfm) and partitioning of the flow rate between sample and recycle flows, the sample orifice for the EGR train requires a smaller diameter to obtain an adequate orifice pressure drop (ΔH). Theoretical and empirical determinations have shown 0.129 in. is a practical diameter for the EGR sample orifice. However, to ensure effective coverage of the range of possible sample flow rates, it is recommended a set of sample orifices be fabricated with the following diameters: 0.180 in., 0.129 in., and 0.094 in. A shop drawing of the EGR orifice set is shown in Appendix B, Figure B-6.

2.2.1.2. Pressure Monitors--

The differential pressure across the sample orifice is monitored by using one leg of a dual-column, partially inclined, water-gauge manometer (Dwyer Instruments, Inc., #422-10). The EGR system uses a 0-10-in. manometer, with an inclined range (0.01-in. divisions) of 0-1.0 in. Accurate reading with an inclined-vertical manometer requires that the inclined portion of the scale be at the exact angle for which it was designed. Therefore, the specified manometer must be mounted to allow alignment as indicated by the integral spirit level. The total and recycle LFE pressure differentials are monitored by using separate magnehelic pressure gauges. The total flow magnehelic gauge spans 0-4.0 in. (Dwyer #2004), and the recycle flow magnehelic gauge spans 0-8.0 in. (Dwyer #2008). The absolute pressure at the inlet to the total LFE must be noted so that the measured flow rates, total and recycle, can be related to the flow rate at stack conditions. To determine this pressure, a magnehelic gauge with a 0-25-in. range (Dwyer #2025) is used to measure the pressure at the specified location, relative to ambient pressure. In practice, the high-pressure tap of this differential pressure gauge is connected in parallel with the high-pressure tap of the total flow LFE, and the low-pressure tap is vented to the ambient pressure. The absolute pressure at the total LFE can then be determined from the sum of the local barometric pressure and the measured inlet relative pressure. Finally, as with a typical Method 5 sampling system, the second leg of the dual inclined manometer is used to measure the pitot (stack velocity) differential pressure. All pressure differential measurement devices are connected to the appropriate pressure taps with 1/4-in. i.d. Tygon tubing (Sargent-Welch S-73651-KC).

The pitot lines enter the control box through two 1/4-in., stainless steel bulkhead compression quick-connect tube fittings. The fittings are coded to distinguish between the high and low pressure lines (red-high, bluelow). This code combination is maintained on all pitot line tube fittings from the control box to the probe. A three-way solenoid valve (Automatic Switch Co. #8314C21) is installed at the control box inlet to each pitot line. The solenoid valves can be toggled to pitot pressures or vented to ambient air for a quick check of the manometer's zero reading. The solenoid valves are connected directly to the appropriate leg of the dual manometer with 1/4-in. Tygon tubing.

2.2.1.3. System Temperature Monitors--

The system temperatures are monitored with type K (Chromel-Alumel) thermocouples. A multiposition switch (Omega #0SW3-10) allows the operator to measure all system temperatures with a single digital meter (Omega #199KF). As a minimum, provisions should be made to monitor the following system temperatures:

- local flue gas temperature,
- heated recycle gas temperature,
- heated probe temperature,
- mixed gas temperature at total LFE,
- sample gas temperature at DGM, and
- local ambient temperature.

The thermocouple connections to the control box are made via a multipin, flanged connector (Omega #MTC-24-FF) for the SRI/EPA prototype EGR system. The pins and sockets of the appropriately compensated metal (Chromel or Alumel) are also used. The power to the probe heating system is controlled through a proportional, 10-A-capacity, temperature controller (Omega #6102-K-0/500 °F). The controller is wired and mounted according to manufacturer's instructions. The controlling thermocouple for the probe heater is housed within the probe assembly, sandwiched between the internal tubing and the heater tape (described in more detail under Section 2.2.4. Sampling/Reheat Probe). A parallel extension from this same thermocouple line (within the control box) is used to visually monitor the probe temperature.

2.2.2. Condenser/Impinger Train

Because the EGR system is typically operated in a Method 17 rather than a Method 5 configuration, the water dropout portion of the prototype EGR system consists of a coiled, stainless steel condenser followed by a drying column. A layout drawing of a typical EGR-type condenser is shown in Appendix B, Figure B-10. The condenser, as well as the required amount of ice, is housed in any appropriate, commercially available ice chest. The drying column should be leak-free and capable of holding 500-600 g of an appropriate desiccant (silica gel, calcium sulfate, etc.). Several commercially available drying columns or towers (Sargent Welch #S-28730) are available. Alternatively, a standard Method 5-type impinger train may be used according to traditional protocol.

2.2.3. Umbilical

As with a standard Method 5 train, the EGR umbilical consists of thermocouple, electrical, pressure, and flow lines bound into a single cable. The only significant difference between a standard Method 5 umbilical and that of the EGR system is the addition of another flow line, the recycle gas line. All flow lines should be fabricated from flexible, durable (abrasive-resistant) tubing. The inside diameter of the total and recycle lines should be sufficient to avoid significant pressure drop through the length of the tubing. The EGR system umbilical uses heavy wall, black neoprene rubber tubing: 3/8-in. i.d. and 1/8-in. wall (Sargent Welch #S-73655-KF). The pitot pressure lines may be fabricated from similar tubing of the appropriate size (Sargent Welch #S73655-KD). For ease of assembly and disassembly during testing, it is suggested quick-connect-type tube fittings be attached to both ends of the umbilical. Furthermore, for stress relief, 90° elbows are recommended for use on the flow lines at the probe end of the umbilical.

The thermocouple and electrical extension lines within the umbilical are made from flexible and durable extension wire of the appropriate type. Although not required, it is strongly recommended that a ground wire be included in the electrical wires to the probe. The ground wire should be coupled to the probe and the system ground at the control box (refer to the Sampling/Reheat Probe section, which follows). The thermocouple and electrical connections at each end of the umbilical may be made by using individual connectors or a single, multipin connector. In either case, the properly compensated connectors should be used.

2.2.4. Sampling/Reheat Probe

In most respects, the EGR sampling/reheat probe is similar to the standard Method 5-type probe. As with a Method 5 probe, the EGR probe houses the pitot extension lines and a heat-traced sample line. A stack gas thermocouple and probe-temperature-measuring thermocouples are also included in the probe assembly. Unlike the Method 5 probe, however, the EGR probe also contains a heat-traced recycle gas line. The sample gas line, referred to as the total flow line within the EGR system, is fabricated from a single length of 5/8-in. stainless steel tubing. The recycle line is fabricated from 1/2-in. stainless tubing, and the pitot lines are 1/4-in. stainless steel tubing. The various tubes are held in place by rigid (weld or silver solder) attachment to an O-ring-sealed probe cap. The O-ring seal between the end cap and the sheath prevents particulate material from entering the probe housing, which would have the potential to create electrical and abrasive problems. A second, loose-fit, end cap supports the out-of-stack end of the tubing. The entire probe assembly is housed within a sheath of 2-in. schedule 5 stainless steel pipe of the appropriate length (the prototype EGR probe sheath is 96 in. long). The 8-ft probe weighs approximately 24 lb.

The heat tracing of the total flow and recycle lines within the probe sheath serves a dual function. As with the Method 5 sample line, the total flow line is heated to prevent unwanted condensation from occurring within the length of the probe. The second function of the heated probe is to warm the recycle gas to stack temperatures to ensure isothermal mixing of the recycle and sample gases at the EGR mixing nozzle. The heated recycle gas temperature is monitored by a thermocouple mounted in-line, immediately upstream of the EGR nozzle (refer to Figure 8). The total and recycle flow lines are heated by using a single, proportionally controlled heater tape (Cole-Parmer #T-3107-80) of the appropriate length. The 1.75-in.-wide heater tape is cupped over both flow lines, spiralling around the tubes several times, and is held securely in place with glass fiber tape. A controlling thermocouple is secured to the recycle line directly beneath the heater tape. Unless the thermocouple is placed in direct contact with both the recycle tube and the heater tape, the system can overheat, causing damage to the assembly. A layer of 1.0-in. x 0.06-in. ceramic fiber cloth tape (Sargent Welch #S-1210-10D) is wrapped completely around the heater tape and appropriate tubing to serve as thermal insulation for the probe assembly. Finally, the insulated, heat-traced tubing is completely wrapped with glass fiber tape for security and protection. The heated assembly, along with the 1/4-in. pitot extension lines, is then housed within the stainless steel sheath.

The external flow extension lines (recycle, pitot) and the specified PM_{10} sampler are attached to the appropriate probe lines by means of commercially available tube compression fittings (e.g., Swagelok, Parker CPI). It is suggested the in-stack fittings be assembled by using stainless steel ferrules for strength and reusability. However, because it may be desirable to disassemble the probe at a future date, Teflon or nylon ferrules are recommended for all tube fittings on the exit end of the probe. These softer ferrules do not cause tubing deformation as do the metal ferrules. This preserves the clearance of the exit probe cap around each tube, allowing smooth disassembly.

It is strongly recommended that the electrical (heater) wires extending from the probe include a ground wire attached to the probe via one of the end cap fastening bolts. Electrical shorts within the heater tape or stray static charges from particulate control devices have been known to cause sampling system interferences and/or damage.

2.2.5. Exhaust Gas Recycle Nozzle

A conceptual design of the stainless steel EGR nozzle can be seen in Figure 10. As is shown, the recycled exhaust gas enters the nozzle through a 1/4-in. side entry tube and fills an annular region around the sample inlet tube. A range of sizes suitable for isokinetic sampling at varying recycle rates should be available, for example, 0.32 to 0.64 cm (1/8 to 1/4 in.) inlet diameter. Furthermore, because inertia tends to cause deposition of particles in the PM_{10} size range in bends, only straight sampling nozzles should be used. "Gooseneck" or other nozzle extensions designed to turn the sample gas flow 90°, as in Methods 5 and 17, should not be used.

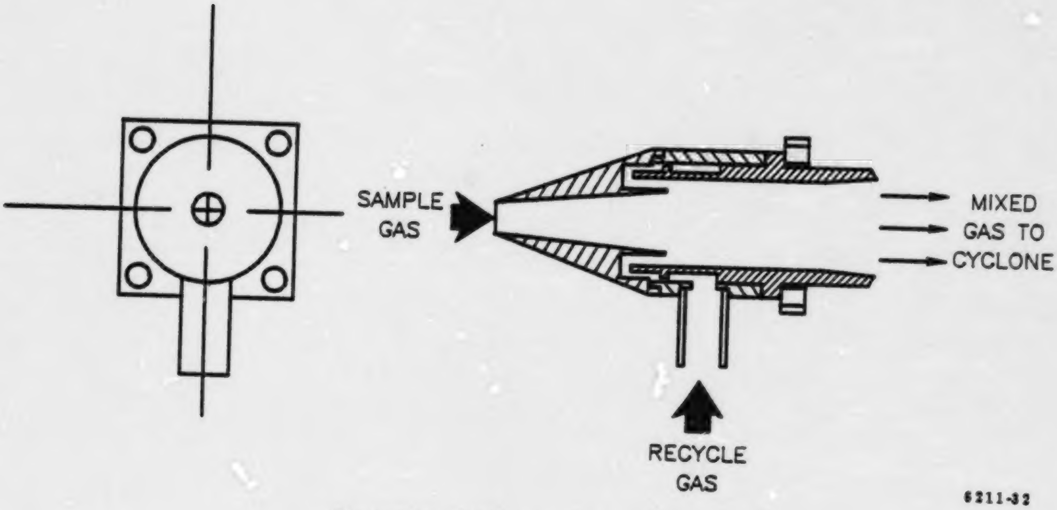


Figure 10. EGR concept nozzle assembly.

Figure 8 shows the recycle line of the system contains a "tee" immediately upstream of the EGR nozzle. The exhaust recycle gas enters the tee through a short section of 1/4-in. stainless steel tubing, bent as required, which is silver-soldered to the branch portion of the tee. The recycle gas exits the tee via one of the "run" end fittings, where the tee is directly connected to the EGR nozzle with compression tube fittings. The second "run" end of the fitting is used to introduce an open-bead, type-K thermocouple to the recycle gas stream. By monitoring the temperature of the recycle gas near the EGR nozzle, isothermal mixing of the recycle and sample gases can be more easily ensured. It is suggested the extension wire for the recycle thermocouple, as well as the stack gas thermocouple, be contained in a braided (stainless steel) sheath for abrasion resistance and durability.

2.2.6 PM_{10} Sampler

The exhaust gas recycle concept has been applied to a single-stage PM_{10} cyclone sampler of a specific geometry. This manual gives specific instruction for this device but does not preclude other cyclones. Before any cyclone is used as a PM_{10} sampler, its performance must be characterized to derive the relationship for the flow rate giving a 10-μm size cut and to verify that performance, including the nozzles, satisfies minimum requirements.

2.2.6.1 Performance Determination for PM_{10} Cyclones--

To determine that a given cyclone meets the requirements for use as a PM_{10} device, the performance determination procedures outlined in the following text must be performed. The objectives of these procedures are twofold: (1) to calibrate the cyclone (i.e., establish the relationship between collection efficiency, flow rate, gas viscosity, and gas density for the given device) and (2) to determine that cyclone performance satisfies the performance specifications with the sampling nozzle geometry used in practice.

Particle generation--The particle generating system used for the performance determination of the sampler must be capable of producing solid, monodisperse dye particles with mass median aerodynamic diameters ranging from 5 to 20 μm. The geometric standard deviation (σ_g) for each particle size should not exceed 1.1. Furthermore, the proportion of multiplets and satellites should not exceed 10% by mass.

The size of the solid dye particles delivered to the test section of the wind tunnel should be established by using the operating parameters of the particle generating system. This should be verified during the tests by microscopic examination of samples of the particles collected on a membrane filter. The precision of the particle size verification technique should be 0.5 μm or better, and the particle size determined in this manner should not differ by more than 10% from that established by the system operating parameters.

The monodispersity of the particles should be verified for each test by either microscopic inspection of particles collected on filters or monitoring techniques such as an optical particle counter followed by a multichannel pulse height analyzer. It is preferable that verification of acceptable particle size distribution be performed on an integrated sample obtained during the sampling period of each test. As an alternative, samples obtained before and after each test may be used to verify the size distribution.

To determine cyclone behavior as a function of gas conditions, the system must be operated at a range of temperatures. The dye particles must withstand temperatures from 22 °C (70 °F) to 200 °C (400 °F) without significant change in size, density, or spectral properties in solution (associated with measurement of collected particulate mass). Ammonium fluorescein (available from a number of sources) has been shown to meet these requirements for temperatures up to 350 °F and Pontamine Fast Turquoise 8GLP (available from E.I. DuPont de Nemours and Company) has been shown to meet them up to 400 °F (Smith et al., 1979). However, the thermal integrity of each dye batch should be verified.

The requirements of the apparatus for heating the monodisperse dye aerosol are illustrated in Figure 11. A pump with an orifice or other flow meter is used to obtain the test flow rate through the cyclone. The combination of absolute filter/bleed valve allows excess aerosol to escape or additional air to enter as needed. The aerosol stream from the generator passes through a copper tube heated to attain the test temperature. The heat transfer rate and uniformity of heating should be sufficient for the aerosol to attain the test temperature but should not cause the temperature of any interior surfaces to rise above the temperature used for verifying the integrity of the dye. The inlet tube to the cyclone must have the same inside diameter as the inlet diameter of the cyclone. This tube must be cleaned between runs and blanks performed to check for possible effects of reentrainment of particles which accumulate on its interior. The sample port is necessary to collect and examine heated particles for correct size, color, and shape for each measurement run.

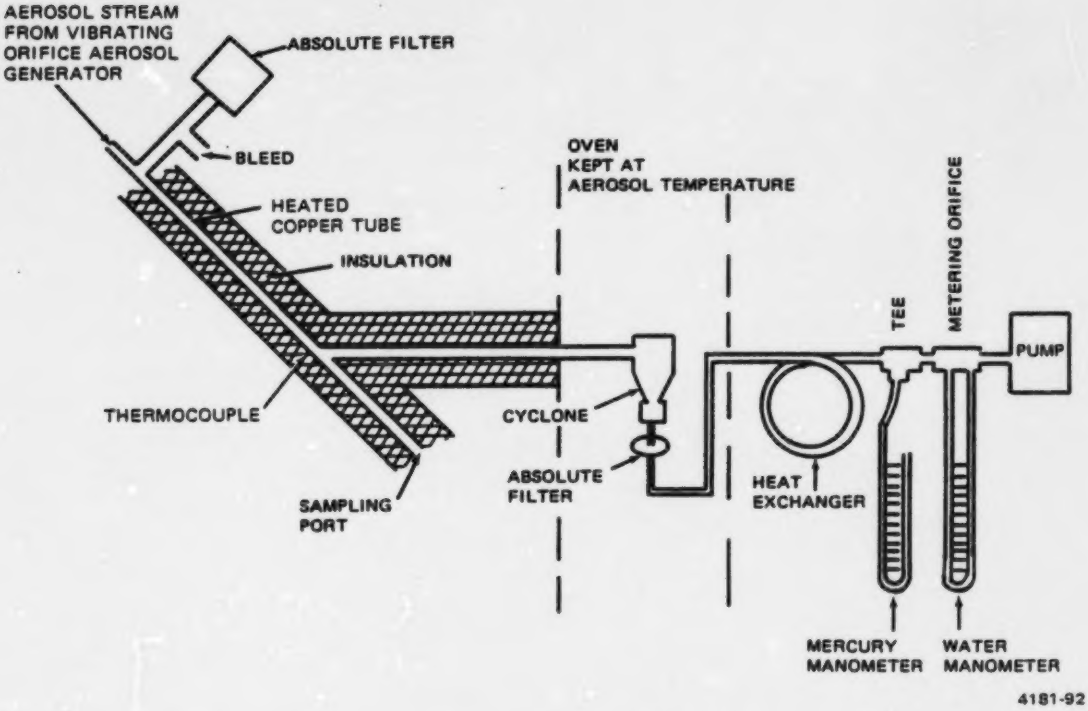

AEROSOL STREAM FROM VIBRATING ORIFICE AEROSOL GENERATOR
ABSOLUTE FILTER
BLEED
HEATED COPPER TUBE
INSULATION
THERMOCOUPLE
SAMPLING PORT
OVEN KEPT AT AEROSOL TEMPERATURE
CYCLONE
ABSOLUTE FILTER
HEAT EXCHANGER
TEE
METERING ORIFICE
PUMP
MERCURY MANOMETER
WATER MANOMETER
4181-92

Figure 11. Calibration system for heated aerosols.

Wind tunnel--A portion of the collection efficiency tests must be performed under isokinetic sampling conditions in a wind tunnel or similar apparatus so that the effect of the sampling nozzle on the cyclone performance may be determined. This apparatus must be capable of establishing and maintaining (within 10%) velocities ranging from 7 to 25 m/s.

The velocity of the wind tunnel gas stream in the vicinity of the sampling nozzle should be measured by using an appropriate technique capable of a precision of 5% or better and of a spatial resolution of 1 cm or less (e.g., hot wire anemometry or miniature pitot tubes). The velocity should be constant within 10% over the inlet area of the largest sample nozzle to be used with the PM_{10} sampler. If the sampler obstructs more than 10% of the wind tunnel cross-sectional area, the velocity uniformity must be demonstrated by velocity measurements with the sampler in position and operating.

For each efficiency test, the gas stream velocity should be determined at the beginning of each test and maintained within 10% of the set value by using a suitable monitoring technique with precision better than 5%.

Cyclone calibration--To achieve the first objective of the performance determination (establish the relationship between collection efficiency, flow rate, and gas conditions) the following procedures should be followed.

The operator should establish operation of the particle generator and verify particle size microscopically. If monodispersity is to be verified by measurements at the beginning and end of the measurement run rather than by an integrated sample, these measurements should be performed at this time. Flow should be initiated through the cyclone at the test value after stable, correct operation of the generator is established. The operator should sample long enough to obtain ±5% precision on total collected mass as determined by precision and sensitivity of the measuring technique. Immediately after completion of sampling, the size of the aerosol particles should be verified microscopically.

The sampled particulate mass is determined by a suitable technique (fluorimetry or absorption spectrophotometry for ammonium fluorescein). The mass collected in the nozzle, PM_{10} sampler body, PM_{10} sampler exit tube, and backup filter (M_{noz}, M_{sam}, M_{et}, M_{fil}, respectively) is determined separately. Each separate surface must be rinsed with an adequate amount of an appropriate solvent to dissolve the collected dye particles, and care must be taken not to contaminate the rinses with dye from other surfaces. Sufficient solvent must be added to each rinse until the rinse volume is suitable for measurement or calculation. It is suggested that the mass of dye in the rinses be determined from spectroscopic or fluorescence measurement by using appropriate blank and standard solutions for reference and quality control.

The total (nozzle and sampler) and sampler-only collection efficiencies (E_{tot} and E_{sam}) may be calculated from the following equations:

$$E_{tot} = 100\% \times (M_{noz} + M_{sam})/(M_{noz} + M_{sam} + M_{et} + M_{fil}) \qquad (2\text{-}1)$$

$$E_{sam} = 100\% \times M_{sam}/(M_{sam} + M_{et} + M_{fil}) \qquad (2\text{-}2)$$

At least two replicates of the above steps should be performed.

The average efficiency should be calculated and recorded as

$$E_t = \frac{\sum_{i=1}^{n} E_{tot}(i)}{n} \qquad E_s = \frac{\sum_{i=1}^{n} E_{sam}(i)}{n} \qquad (2\text{-}3)$$

where $E_{tot}(i)$ and $E_{sam}(i)$ represent individual E_{tot} and E_{sam} values and n equals the number of replicates.

The standard deviation (S) for the replicate measurements should be calculated and recorded as

$$S = \left[\frac{\sum_{i=1}^{n} E^2(i) - \left(\sum_{i=1}^{n} E(i) \right)^2 / n}{n - 1} \right]^{0.5} \qquad (2\text{-}4)$$

where E(i) represents $E_{tot}(i)$ and $E_{sam}(i)$.

For $n = 2$, $S = [E(1) - E(2)]/\sqrt{2}$. If the value of S for E_{tot} exceeds 10% of E_t, the test run must be repeated.

The size cut, D_{50}, of the cyclone is established by either of two sets of measurements. In one set, operating conditions are adjusted to obtain a collection efficiency, E_s, of 50 ±5% for a single particle size. Three replicate runs should be performed with the actual particle size for each run within ±5% of the average value. In the other set, E_s is measured with at least three particle sizes at the same operating conditions, and linear interpolation in log-probability space is used to determine the D_{50}. In the latter set, the measured E_s values must be between 20 and 80% and include values both below and above 50%.

PM_{10} Flow rate--To determine the empirical relationship between PM_{10} flow rate and gas conditions, the D_{50} determination described above must be performed for at least three temperatures. The D_{50}'s must be between 5 and 15 µm and measured at temperatures within 60 °C (108 °F) of the temperature at which the cyclone will be used. In addition, one of the measured D_{50}'s must be 10 ± 0.5 µm.

Linear regression analysis is used to determine the relationship between the dimensionless parameters Ψ_{50} ($\equiv$ 0.5 Stk_{50}) and Re, where Stk_{50} is the Stokes number giving 50% collection and Re is the Reynolds number of the gas entering the cyclone.

$$\Psi_{50} = 0.5\, Stk_{50} = D_{50}{}^{2} \frac{4Q}{18\pi\mu d^{3}} \tag{2-5}$$

and

$$Re = \frac{4\rho Q}{\pi\mu d} \tag{2-6}$$

where Q = gas flow rate through the cyclone at the inlet conditions
μ = gas viscosity
d = diameter of the cyclone inlet
ρ = gas density at the cyclone inlet

With the substitution of D_{50} = 10 µm into the resulting relationship, the flow rate for PM_{10} measurements is predicted as a function of gas conditions.

Determination of cyclone/nozzle collection efficiency--Because the cyclone and sampling nozzles are used as a unit in actual sampling situations, it is necessary to establish that the nozzles do not perturb the particle sizing characteristics of the cyclone as determined by the calibration procedures discussed previously. To do this, collection efficiency tests should be performed for the cyclone/nozzle unit by using the particle diameters and gas velocities shown in Table 1. For the appropriate PM_{10} sampler flow rate, the operator should determine the nozzle size appropriate for isokinetic sampling in each of the three velocity ranges shown in the table. If more than one nozzle is suitable for a range, the larger nozzle may be chosen.

TABLE 1. PARTICLE SIZES AND NOMINAL GAS VELOCITIES FOR EFFICIENCY PERFORMANCE TESTS OF CYCLONES

Particle Size (μm)[a]	Target Gas Velocity (m/s)		
	7 ± 1.0	15 ± 1.5	25 ± 2.5
5 ± 0.5			
7 ± 0.5			
10 ± 0.5			
14 ± 1.0			
20 ± 1.0			

[a] Mass median aerodynamic diameter.

Number of test points (minimum of two replicates for each combination of gas velocity and particle size): 30.

After the three nozzle sizes have been determined, the first airstream velocity to be tested in the wind tunnel should be established and verified as described previously. The particle generating system should then be started and the particle size distribution verified. The particle size, as determined by the system operating conditions, must be within the tolerances specified in the table. The operator should begin sampling by establishing the flow rate required for a 10-μm D_{50} in the cyclone.

At the completion of the runs, the total and sampler-only collection efficiencies (E_{tot} and E_{sam}) should be determined from equations 2-3 and 2-4. For each of the three gas stream velocities tested, the average E_t and E_s should be plotted as functions of particle size (D). Smooth curves should be drawn through all sizes used. The D_{50} for E_s should be defined as the diameter at which the E_s curve crosses 50% efficiency.

2.2.6.2 Performance Specifications for PM_{10} Cyclones--

The performance specifications for a PM_{10} cyclone are shown in Table 2. To be acceptable for use, the D_{50} for the sampler (determined from the E_s curve as described previously) must be 10 ± 1 μm. In addition, all data points used to determine the E_t curves for each of the gas stream velocities tested must fall within the banded region shown in Figure 12. The portion of the acceptance envelope corresponding to large particles is bounded by a vertical line at 12 μm, a horizontal line at 90% efficiency, and a lognormal function (oblique line) with geometric standard deviation (σ_g) of 1.7 and 50% efficiency at 12 μm. The boundary at small particle sizes has a vertical line at 8 μm and horizontal lines and lognormal functions which vary between three ranges of gas stream velocity. These horizontal lines are at 10, 20, and 30% efficiency, respectively, with increasing gas velocity. At the lowest range of velocity the lognormal function has σ_g of 1.7 and 50% efficiency at 8 μm. For the two higher velocity ranges, the lognormal functions have 55% efficiency at 8 μm and values of σ_g of 2 and 2.9, respectively, with increasing gas velocity.

TABLE 2. PERFORMANCE SPECIFICATIONS FOR SOURCE PM_{10} SAMPLERS--CYCLONES

Parameter	Units	Specification
1. Collection Efficiency	%	Such that collection efficiency falls within envelope specified in Figure 12
2. Sampler 50% cut point (D_{50})	μm	10 ± 1 μm aerodynamic diameter

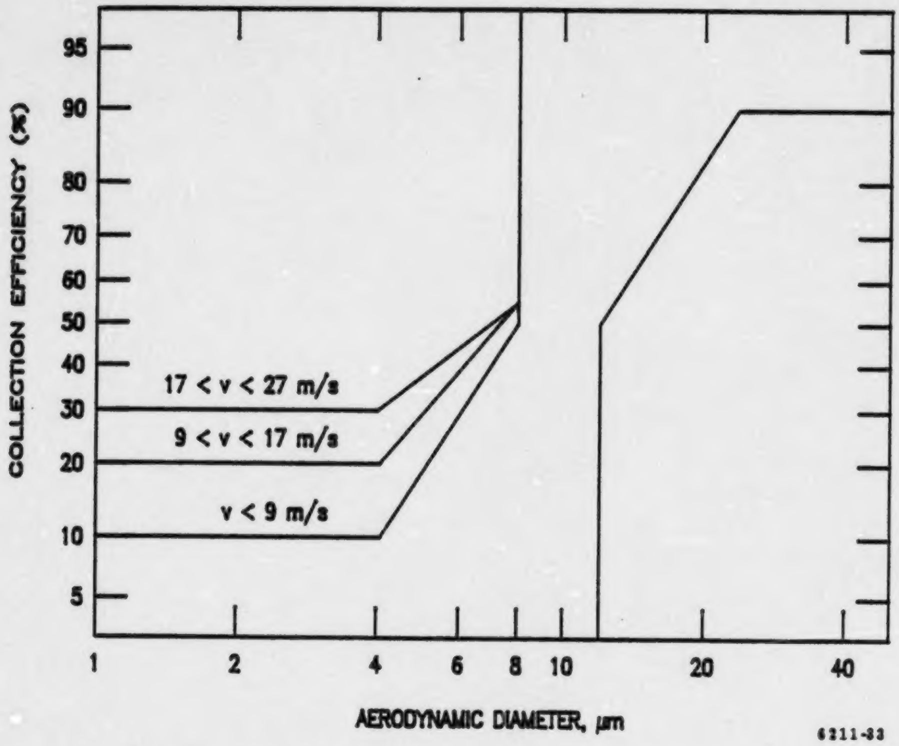


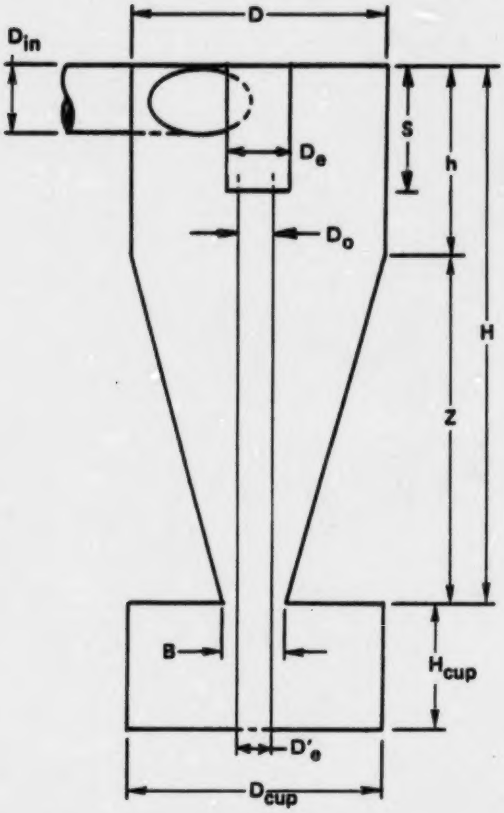
Figure 12. Efficiency envelope for PM$_{10}$ sampler.

2.2.6.3 Recommended PM$_{10}$ Cyclone Sampler--

The PM$_{10}$ sampler specifically described in this manual is the commercially available version of Cyclone I, the first stage of the SRI/EPA five-stage series cyclone (Smith et al., 1979). The cyclone is available in a variety of outer dimensions and styles from different commercial sources. The critical inner dimensions, however, are standardized to the original design parameters, as can be seen in Figure 13. The EGR sampling nozzle is attached to the stainless steel cyclone body with a flange plate or straight pipe threads. Laboratory calibrations (Farthing and Williamson, 1985) have shown Cyclone I produces a 10-µm fractionation at a flow rate of approximately 0.5 dscfm; the precise flow rate depends on local stack conditions.

CYCLONE I DIMENSIONS

BOTTOM EXIT


D
D_{in}
D_e
S
h
D_o
H
Z
B
H_{cup}
D'_e
D_{cup}

	DIMENSIONS (in. ± 0.01; cm ± 0.02)											
	D_{in}	D	D_e	B	H	h	Z	S	H_{cup}	D_{cup}	D'_e	D_o
cm	1.27	4.47	1.50	1.88	6.95	2.24	4.71	1.57	2.25	4.45	1.02	1.24
in.	0.50	1.76	0.59	0.74	2.74	0.88	1.85	0.62	0.89	1.75	0.40	0.49

5695-71A

Figure 13. Cyclone I dimensions.

SECTION 3

CALIBRATION

As in Method 5 or Method 17, calibration of specific components of the EGR sampling system is required. A notebook or other record should be kept of all calibration data pertinent to each EGR system. This record should contain the complete calibration history of each device requiring such service (i.e., flow metering devices, pitot tubes, nozzles, thermocouples, and magnehelic gauges). A separate record may be desirable for support equipment such as balances and field barometers, which are not directly connected with the EGR system.

3.1. FLOW METERING SYSTEM

The best calibration of a flow metering device is achieved when the calibration data are restricted to the range of expected use. The defined Method 5 flow rate of 0.75 dscfm provides a finite range of flow rates over which the flow metering system should be calibrated. However, the PM_{10} flow rate depends on the characteristics of the sampler used and cannot be easily defined as a single value. This makes defining a calibration range for the flow metering devices difficult at best. For the purposes of this manual, the PM_{10} flow rate at typical meter box conditions is assumed to be 0.50 acfm. For EGR sampling, the range of potential sample flow rates then becomes 0.1 to 0.5 acfm. The investigator must determine the applicability of these flow ranges to his particular system.

The four flow metering devices of the EGR system (dry gas meter, sample orifice, total LFE, and recycle LFE) should undergo a stringent laboratory calibration prior to field use. Thereafter, the calibration should be checked after each test series. This calibration check procedure ensures that the calibration parameters assigned to the flow metering devices are still valid without requiring the level of effort of the initial calibration. Should the results of the calibration check fall outside acceptable limits, the flow metering device in question should be recalibrated by using the initial calibration procedure.

A leak check of the flow metering system should be performed before calibration. The leak check of the vacuum (negative pressure) system should be performed according to the following procedure:

1) turn on the pump, close the recycle valves, and completely open the total flow, fine-adjust valve;
2) plug the sample inlet of the control console, and adjust the total flow, fine-adjust valve until a vacuum of 25 in. Hg is achieved;
3) observe the gas meter reading for 1 min.

If the gas meter registers a leak rate in excess of 0.005 cfm, the leaks must be found and corrected until the above specifications are met.

The positive pressure side of the system should also be leak checked, from the vacuum pump to the sample orifice and recycle outlets, according to the following procedure:

1. open the recycle valves and close both the total flow, coarse- and fine-adjust valves;
2. plug the vacuum pump exhaust at the inlet to the control console (if a quick disconnect with a leak-free check valve is used here, a plug will not be needed;
3. plug the recycle gas outlet;
4. place a one-hole rubber stopper with a tube through the hole in the outlet of the sample orifice.
5. attach latex or similar tubing to the tube;
6. blow into the tubing until a pressure of approximately 20 in. H_2O is registered on the total LFE inlet pressure magnehelic gauge;
7. observe the gauge reading for 1 min.

If a loss in pressure occurs, a leak(s) is present in the system. All leaks should be corrected before calibration.

A calibrated wet test meter or any other such calibration standard should be used to calibrate the EGR flow metering system. The outlet of the calibration standard should be connected to the sample inlet of the control console. Before the calibration is started, the EGR vacuum pump should be run for 15 min with the orifice meter ΔH set at approximately 0.5 in. H_2O to allow the pump to warm up and to wet the interior surface of the wet test meter.

Calibration of the EGR flow metering system must be performed in two separate steps, the second step being the calibration of the recycle system components. Calibration of the dry gas meter, sample orifice and total flow LFE should be performed as follows:

1) close the recycle valves and open the back-pressure valve;
2) perform the calibration as required in EPA Reference Method 5 for a range of orifice ΔH settings: 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 in. H_2O (the minimum wet test meter volume for each run should be 5.0 ft^3, except for the two lowest flow rates where a volume of 3.0 ft^3 is acceptable).
3) record the total LFE pressure differential, inlet pressure, and temperature, in addition to the data requested in Method 5.

To effectively cover the range of possible sample flow rates, a set of orifices is recommended. Suggested orifice diameters are given in Section 2. Calibration of the complete set should be performed before testing. For each orifice, the calibration procedure should be performed by using the ΔH settings listed above, neglecting those that fall outside the sample flow range described previously.

The recycle LFE should be calibrated as follows:

1) open both recycle valves and close the back-pressure valve;
2) perform the calibration procedure for recycle ΔP values of 0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 in. H_2O (the minimum wet test meter volume for each run should be 3.0 ft^3);
3) record the recycle LFE pressure differential, inlet pressure, and temperature, as well as the wet test meter volume, temperature and calibration run time.

The calibration constants for the dry gas meter and orifice (γ and $\Delta H@$, respectively) should be calculated as outlined for Method 5. The behavior of the total and recycle LFEs may be best described by the equation

$$Q = S\Delta P \left(\frac{\mu_{ST}}{\mu_L}\right) + W \qquad (3-1)$$

where μ_{ST} = viscosity of standard air (180.1 micropoise),
μ_L = viscosity of sample gas (micropoise), and
S,W = linear calibration constants.

The calibration constants S and W may be obtained by plotting the calibration data points and determining the best-fit line. A linear regression on the data is another alternative.

A calibration check should be performed on all of the flow metering devices after each field test series. The posttest calibration check should consist of three calibration runs at a single orifice setting. This orifice setting should be representative of the orifice settings used during the field test. The run procedure should be the same as described for the initial calibration of the dry gas meter, orifice, and total flow LFE. At the end of each run,

1) record the final wet test meter and dry gas meter readings,
2) restart the pump without changing the total flow settings,

3) open both recycle valves and close the back-pressure valve,
4) record the pressure differential across the recycle LFE.

If the dry gas meter calibration factor, γ, deviates by less than 5% from the initial calibration factor, then the calibration constant assigned to the meter is still valid. If the posttest calibration check yields a calibration factor outside this limit, the gas meter should be recalibrated by using the initial calibration procedure.

The average pressure drops across the sample orifice, total LFE, and recycle LFE recorded during the calibration check should be compared with those obtained from the calibration equation for each device. The ΔP is calculated from the calibration equation by using the wet test meter flow rate corrected for temperature and pressure at each of the devices. If the recorded ΔPs vary from the calculated values by more than 10%, the flow metering device should be recalibrated.

If either the dry gas meter or total flow LFE requires recalibration, for the purposes of data reduction, use whichever coefficient (initial or recalibrated) yields the lower gas meter volume and higher cyclone flow rate.

3.2. PITOT TUBE

The construction, configuration, and calibration specifications outlined in EPA Reference Method 2 (U.S. EPA, 1977) should be applied to the EGR pitot tube. The pitot tube should be located at the side of the nozzle furthest from the axis of the PM_{10} sampler. To check the pitot tube for leaks, one end of the tube should be plugged and a positive pressure applied at the opposite end. If the tube will not maintain pressure, a soap solution can be used to identify the location of any leaks. The EGR pitot tube is calibrated by measuring the velocity pressure, ΔP, at the same point within a cross-section of a straight run of ductwork with a standard pitot tube and with the S-type EGR pitot tube for a desired range of gas velocities. The EGR pitot tube should be calibrated as used; that is, the complete sampler assembly should be used in pitot tube calibration determinations. The EGR pitot tube should be calibrated twice, as recommended in Method 2, with the direction of the legs reversed during the second calibratrion. For each velocity, determine a pitot tube coefficient as

$$C_p = 0.99 \left(\frac{\Delta P_{STD}}{\Delta P_{EGR}}\right)^{1/2} \qquad (3\text{-}2)$$

where C_p = EGR S-type calibration coefficient, dimensionless;
0.99 = C_p value for standard pitot tube, dimensionless;
ΔP_{STD} = velocity pressure drop of standard pitot tube, inches of water; and
ΔP_{EGR} = velocity pressure drop of EGR S-type pitot tube, inches of water.

The average value of C_p for each direction over the range of velocities used should be calculated.

3.3. EGR NOZZLES

The EGR nozzles are calibrated in the following manner:

1) use a micrometer to measure the inside diameter of the EGR nozzle to the nearest 0.001 in.;
2) make four separate measurements by using different diameters each time and obtain the average of the measurements.

The largest deviation from the average should not exceed 0.004 in. If the variation is more than 0.004 in., the nozzle should be reshaped and recalibrated.

3.4. THERMOCOUPLES

The thermocouples used to measure the various temperatures within the EGR sampling train (Chromel-Alumel; type K) should be checked for proper calibration before installation in the system. A two-point calibration check with an ice bath and a boiling water bath should be performed as outlined in EPA Reference Method 2. If any individual thermocouple does not produce a reading within 3° of the expected value, it should be replaced with another thermocouple of the same type. If all thermocouples show a bias, the readout should be adjusted or recalibrated according to the manufacturer's procedure.

3.5. MAGNEHELIC GAUGES

The calibration of the magnehelic differential pressure gauges should be checked before field use and periodically thereafter to prevent invalidation of test data. Before its calibration is checked, the magnehelic gauge should be zeroed by using the external zero-adjust screw. A calibration check is performed by comparing ΔP values, as read from the magnehelic gauge, with those from an inclined manometer at a minimum of three points. The ΔP values read from the magnehelic gauge should not deviate from the inclined manometer readings by more than 5% at any point.

3.6. SUPPORT EQUIPMENT

The field barometer should be adjusted initially and before each test series to agree with a standard (a mercury-in-glass barometer or the pressure reported by a nearby National Weather Service station) to ±0.1 in. Hg.

The calibration of all balances to be used during a test series should be checked initially with Class-S weights. Trip balances should be within ±0.5 g of the standard. Analytical balances should agree to ±2 mg of the standard. Balances that fail to meet these criteria should be adjusted or returned to the manufacturer.

SECTION 4

PRESAMPLING ACTIVITIES

Preparation of the EGR sampling system for field use requires much the same effort as preparation for Method 5 or Method 17 sampling. Some type of pretest calibration or operation check is necessary for most components of the system. This is also true of supporting equipment such as analytical balances. Sampling reagents also require preparation before field use. In several cases, the presampling activities described below are very similar to or the same as those required for Method 5.

4.1. EQUIPMENT CALIBRATION AND CHECKS

All EGR sampling nozzles should be inspected for damage and repaired where necessary. The nozzles should be cleaned with tap water, deionized water, and finally acetone. The dimension of the inside diameter of each nozzle should be determined to the nearest 0.001 in. as described in Section 3 of this manual. The knife edge of the nozzle should be protected during shipment by serum caps or similar covers.

The PM_{10} sampler and filter holder should be ultrasonically cleaned with tap water and rinsed with deionized water. After a final rinse with acetone, the sampler assembly should be allowed to air dry. An adequate supply of Viton or silicone rubber O-rings should be available for replacement of worn O-rings in these devices.

The openings of the pitot tube should be inspected for damage such as dents or nicks. A check should also be made for proper alignment. The two legs of the pitot should be in a straight line so that the opening of one leg is directed 180° from the other. If damage or misalignment is evident, the pitot tube should be repaired or replaced. If repairs are made, the pitot tube should be recalibrated, as described in Section 3.

All lines of the EGR probe, including the recycle and pitot lines, should be cleaned before field use. The lines should be cleaned internally by rinsing, first with tap water, then deionized water followed by acetone. The lines should be rinsed a final time with acetone and allow to air dry. The probe heating system should be checked for proper operation. If problems are encountered, the operator should refer to Section 10 of this manual for troubleshooting guidelines.

The water dropout system (condenser and drying column) should be checked for leaks. The condenser should be cleaned with deionized water and rinsed with acetone. The condenser should be inverted to ensure total drainage and allowed to air dry.

The system flow metering devices (dry gas meter, orifice, total LFE, and recycle LFE) should have appropriate calibration factors assigned to them. A pretest calibration check, performed with the procedure outlined for posttest calibration checks in Section 3, is recommended to ensure the calibrations are still valid. Although pretest calibration checks of the flow metering devices are not required and do not take the place of the posttest checks, they are useful for detecting problems before field use. Such a pretest calibration check is strongly recommended if the system has not been used for some time.

It is recommended, but not required, that the calibration of the magnehelic pressure differential gauges be checked prior to field sampling. As with the flow metering system, this is strongly suggested if the system has not been used for an extended period of time.

All system temperature sensors (thermocouples, temperature gauges, etc.) should be checked against a mercury-in-glass thermometer at ambient temperature.

Finally, it is recommended that a leak check of the complete system be performed before it is shipped to the field. The system should be assembled from the probe (it is not necessary to include the EGR nozzle or PM_{10} sampler) to the control console. The probe should be capped and the system leak-checked at 15 in. Hg vacuum. Leak check in excess of 0.02 cfm should be corrected. Each leg of the pitot tube, including the umbilical lines and the differential pressure gauge, should be leak-checked.

4.2. PREPARATION OF SAMPLING REAGENTS

Used silica gel should be regenerated by drying at 350 °F for 2 h. New silica gel may be used as received. Several 200- to 300-g portions may be weighed in airtight containers to the nearest 0.5 g. The total weight for each container should be recorded. As an alternative, the silica gel may be weighed in the drying column at the test site.

Filters should be desiccated and weighed as required for EPA Reference Method 5. To prevent the loss of filter cake, it is recommended that aluminum foil envelopes be made to enclose the filter. If used, these envelopes should be desiccated and weighed with the filter.

Aluminum foil envelopes can also be used to collect the PM_{10} cyclone catch. These foil envelopes should be uniquely identified, desiccated, and weighed in the same manner as the filters.

Acetone for sample recovery should be reagent grade with less than 0.001% residue. Acetone blank determinations to ensure residue levels are acceptable may be made before field use or as part of sample recovery.

SECTION 5

SAMPLING PARAMETERS

During Method 5 sampling, the operator must be able to convert the velocity pressure and stack temperature at multiple traverse points into the sample flow rate needed to maintain isokinetic sampling. This flow rate is then translated to a pressure differential across the sample orifice which the operator can adjust. There are a variety of methods (nomographs, hand calculator programs, etc.) for doing this in a few simple steps.

Isokinetic sampling must also be maintained with the EGR system. However, the EGR system introduces complications in the form of additional flow rates that must be monitored in the same manner as the sample flow rate. This section describes two methods for accomplishing this objective. The first method described provides an exact solution to the governing equations. The multiple iterations required to obtain this solution have prompted the development of the second method, an approximate solution to the equations that avoids the necessity of iterations.

5.1. PRELIMINARY MEASUREMENTS

Before the appropriate sampling parameters can be calculated for the EGR system, some type of preliminary determination of the stack gas conditions must be made. Stack temperature and velocity profiles of the sampling plane may be obtained from Method 2 data. This information is necessary for the EGR setup and nozzle selection calculations discussed later in this section.

The concentration of the primary stack gas constituents (i.e., oxygen, carbon dioxide, nitrogen, carbon monoxide, and water vapor) may be determined from Method 3 and Method 4 data. With this information, the gas dry and wet molecular weights (M) may be determined from the following equations:

$$M_d = 32(f_o) + 44(f_c) + 28(1 - f_o - f_c) \tag{5-1}$$

$$M_w = M_d(1 - B_{ws}) + 18\ B_{ws} \tag{5-2}$$

where B_{ws} = the water fraction.

It may be necessary to perform additional methods in cases where the stack gas composition is influenced by gases other than those listed above. For example, when sampling gases from a high-sulfur source, Method 8 should be performed to determine the percentage of H_2SO_4 present in the gas as vapor and the acid dew point.

The viscosity (μ)of the flue gas can be determined by the equation (Williamson et al., 1983)

$$\mu = C_1 + C_2T + C_3T^2 + C_4B_{ws} + C_5f_o \tag{5-3}$$

where μ is in micropoise, T in °C, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = 74.143$
$C_5 = 53.147$

or for T in °R

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = 74.143$
$C_5 = 53.147$

This equation fits data (with a standard error of 0.98 micropoise) for combustion gas of arbitrary composition in the range 0-350 °C, 0-70% moisture. This equation was generated by SRI personnel from large "data banks" of viscosities calculated by the more rigorous algorithm of Wilke (1950). Finally, the location of the traverse points should be determined as outlined in Method 1.

5.2. EGR FLOW RATES

The flow rates of interest in the EGR system are the sample flow rate (Q_s), total flow rate (Q_t), and, of secondary interest, the recycle flow rate (Q_r). At each point of a sample traverse, these three flow rates must be determined and then converted to pressure differentials across the appropriate flow metering device.

The sample flow rate may be determined in the same manner as in Method 5 from the equation

$$Q_s = \frac{\pi d_n^2}{4} V_s \tag{5-4}$$

The total flow rate through the PM_{10} sampler is, in principle, fixed by the characteristics of the sampler. For SRI/EPA Cyclone I, the flow rate equation for a 10-μm cut diameter takes the form

$$Q_t = 0.002837 \left(\frac{M_w P_s}{T_s}\right)^{-0.2949} \mu \tag{5-5}$$

Unfortunately, equation 5-5 cannot be solved in a straightforward manner because the wet molecular weight and viscosity terms are dependent on the amount of moisture in the total flow. This cannot be easily determined because the total flow through the cyclone is a mix of sample gas (with a known moisture fraction) and recycle gas (dry). Solution of this equation requires iterations of Q_t until a desired resolution is achieved. Once Q_t has been determined in this manner, the recycle flow rate may be calculated as the difference between the total and sample flow rates.

As an alternative to the solution described above, an approximation may be made that avoids the necessity of iterations on Q_t. Such an approximation may take several forms. Of primary importance is the accuracy of the approximate solution over the range of potential sampling conditions. The total flow approximation discussed below agrees with the exact solution of the equation to ±1% for stack temperatures ranging from 100 to 500 °F and stack gas moisture up to 50%.

During a sample traverse, the total flow through the PM_{10} sampler at any given time is a mix of moist sample gas and dry recycle gas. First, Q_w is defined as the PM_{10} sampler flow rate when the total flow is composed entirely of sample gas with a known moisture fraction (zero percent recycle). At the other limit, Q_d is defined as the PM_{10} sampler flow rate when the total flow is composed entirely of dry recycle gas (100% recycle). Q_t must fall somewhere between these two extremes. A linear interpolation between Q_w and Q_d provides an approximate solution for Q_t, which takes the form

$$Q_t = Q_d - \frac{Q_s (Q_d - Q_w)}{Q_w} \tag{5-6}$$

5.3. TARGET PRESSURE DIFFERENTIALS (ΔH, ΔP_t, ΔP_r)

When all three flow rates have been determined, the pressure differentials across the flow metering devices must be determined for each flow rate. The sample orifice ΔH may be calculated in the same manner as in Method 5. The pressure drop across the total and recycle LFEs may be found by using the calibration equation, corrected for local conditions, presented in Section 3. For the total flow LFE,

$$\Delta P_t = \frac{\mu_L}{\mu_{ST}} \left[\frac{1}{S_t} \frac{P_s}{P_L} \frac{T_M}{T_s} (Q_t - Q_s B_{ws}) - \frac{W_t}{S_t} \right] \tag{5-7}$$

Similarly, for the recycle LFE,

$$\Delta P_r = \frac{\mu_L}{\mu_{ST}} \left[\frac{1}{S_r} \frac{P_s}{P_L} \frac{T_M}{T_s} (Q_t - Q_s) - \frac{W_r}{S_r} \right] \tag{5-8}$$

Although an exact solution of equations 5-7 and 5-8 could be obtained iteratively, it is only necessary to utilize the approximate solution for Q_t. Using the approxim solution given in equation 5-6, the term of interest in equation 5-7 is

$$Q_t - Q_s B_{ws}$$

By using the approximation for Q_t given above, this becomes

$$Q_t - Q_s B_{ws} \cong Q_d - \frac{Q_s (Q_d - Q_w)}{Q_w} - Q_s B_{ws}$$

$$\cong Q_d - Q_s \left(\frac{Q_d}{Q_w} + B_{ws} - 1 \right) \tag{5-9}$$

From the flow rate equation for the PM_{10} sampler (equation 5-5) and the definitions given previously, we can obtain equations for Q_w and Q_d.

$$Q_w = 0.002837 \left(\frac{M_w P_s}{T_s} \right)^{-0.2949} \mu_w \tag{5-10}$$

$$Q_d = 0.002837 \left(\frac{M_d P_s}{T_s} \right)^{-0.2949} \mu_d \tag{5-11}$$

where μ_w is the sample gas viscosity and μ_d is the recycle gas viscosity.

Taking the ratio of these two flow rates and simplifying

$$\frac{Q_d}{Q_w} = \left(\frac{M_d}{M_w}\right)^{-0.2949} \frac{\mu_d}{\mu_w} \tag{5-12}$$

By solving M_w and μ_w in terms of M_d and μ_d and substituting into the above equation

$$\frac{Q_d}{Q_w} = \left[1 - B_{ws}\left(1 - \frac{18}{M_d}\right)\right]^{0.2949} \left[\frac{\mu_d}{\mu_d - 74.143B_{ws}}\right] \tag{5-13}$$

Performing a binominal expansion on the first term of this equation yields

$$\left[1 - B_{ws}\left(1 - \frac{18}{M_d}\right)\right]^{0.2949} \cong 1 + 0.2949 \left[-B_{ws}\left(1 - \frac{18}{M_d}\right)\right] \tag{5-14}$$

After substituting into equation 5-13 and simplifying, we have

$$\frac{Q_d}{Q_w} = \frac{\left[B_{ws}\,\mu_d\left(1 - 0.2949\left(1 - \frac{18}{M_d}\right)\right) + 74.143\,B_{ws}(1 - B_{ws})\right]}{\mu_d - 74.143\,B_{ws}} \tag{5-15}$$

Finally, to obtain the pressure differential across the total flow LFE, which corresponds to total flow, Q_t, in the PM_{10} sampler, we apply the equations for Q_s (equation 5-4), Q_d (equation 5-11), and Q_d/Q_w (equation 5-12) to equation 5-15. The result is the expression for ΔP_t shown below:

$$\Delta P_t \cong \frac{K_1}{S_t(T_s)^{0.7051}} - \frac{K_2K_3}{S_t\sqrt{T_sM_w}}\sqrt{\Delta P_{vel}} - \frac{\mu_L\,W_t}{180.1\,S_t} \tag{5-16}$$

where

$$K_1 = 1.5752 \times 10^{-5} \frac{\mu_L T_M}{P_L} \frac{P_s^{0.7051}}{M_d^{0.2949}} \mu_d$$

$$K_2 = \frac{0.1539 \mu_L T_M d_n^2 C_P}{P_L} \sqrt{P_s}$$

$$K_3 = \frac{\left[B_{ws} \mu_d \left(1 - 0.2949 (1 - \frac{18}{M_d})\right) - 74.143 B_{ws} (1 - B_{ws})\right]}{\mu_d - 74.143 B_{ws}}$$

Taking a similar approach for the recycle LFE pressure differential, we see that the term of interest in equation 5-8 is

$$Q_t - Q_s$$

Applying the Q_t approximation,

$$Q_t - Q_s \cong Q_d - \frac{Q_s (Q_d - Q_w)}{Q_w} - Q_s$$

$$\cong Q_{dry} - Q_s \left(\frac{Q_d}{Q_w}\right) \qquad (5\text{-}17)$$

Following the steps discussed previously to determine ΔP_t, the equation for ΔP_r becomes

$$\Delta P_r \cong \frac{K_1}{S_r (T_s)^{0.7051}} - \frac{K_2 K_4}{S_r \sqrt{T_s}} \sqrt{\Delta P_{vel}} - \frac{\mu_L W_r}{180.1 S_r} \qquad (5\text{-}18)$$

where

$$K_1 = 1.5752 \times 10^{-5} \frac{\mu_L T_M}{P_L} \frac{P_s^{0.7051}}{M_d^{0.2949}} \mu_d$$

$$K_2 = 0.1539 \frac{\mu_L T_M d_n^2 C_p}{P_L} \sqrt{P_s}$$

$$K_4 = M_w^{-0.2051} M_d^{-0.2949} \left(\frac{\mu_d}{\mu_d - 74.143B_{ws}}\right)$$

Although equations 5-16 and 5-18 appear cumbersome to use, several of the terms represented are constants, or essentially so, over the time span of a sampling traverse. Some preliminary calculations can, therefore, reduce these equations to much simpler functions. These, in turn, can be used by the operator to calculate the target pressure differentials for the flow metering devices at each traverse point.

The worksheets shown in Figures 14 through 16 were developed for this approach to the EGR setup calculations. The target value for sample orifice ΔH is obtained in Figure 17 by using the standard equation from Method 5. The total and recycle flow LFE pressure differentials are determined by the approximate solutions shown as equations 5-16 and 5-18. The worksheets determine simplified equations for ΔH, ΔP_t, and ΔP_r such that

$$\Delta H = A_o \Delta P_{vel}$$

$$\Delta P_t = A_t - B_t \sqrt{\Delta P_{vel}}$$

$$\Delta P_r = A_r + B_r \sqrt{\Delta P_{vel}}$$

In addition to the worksheets, a program for the Hewlett Packard Calculator HP41C® has been written that takes this same approach to the EGR setup calculations. A listing of the program is included as Appendix D of this manual.

EGR WORKSHEET I

ORIFICE ΔH

Barometric Pressure, P_a, in. Hg = ____________________

Stack Differential Pressure, D_p Stack, in. H_2O = ____________________

Average Stack Temperature, T_s, °R = ________________

Meter Temperature, T_M, °R = __________________

Gas Analysis:

CO_2 Fraction, f_c = ______________
O_2 Fraction, f_o = ______________
Water Fraction, B_{ws} = ____________

Calibration Data:

Nozzle Diameter, d_n, in. = ____________
Pitot Coefficient, C_p = ____________
$\Delta H_@$ = ______________

$M_d = 44(f_c) + 32(f_o) + 28\ (1 - f_c - f_o) =$ ____________________

$M_w = M_d\ (1 - B_{ws}) + 18(B_{ws}) =$ __________________

$P_s = P_a + \dfrac{D_p \text{ Stack}}{13.6} =$ ______________________

$A_o = 846.72\ d_n^4\ \Delta H_@\ C_p^2\ (1 - B_{ws})^2\ \dfrac{M_d\ T_M\ P_s}{M_w\ T_s\ P_a} =$ __________________

$\Delta H = A_o\ \Delta P_{vel}$

= _________________________

Figure 14. EGR setup calculation worksheet I: orifice ΔH.

EGR WORKSHEET II

TOTAL FLOW LFE ΔP

Barometric Pressure P_a, in. Hg = ____________

Stack Differential Pressure, D_p Stack, in. H_2O = ____________

Average Stack Temperature, T_s, °R = ____________

LFE Temperature, T_M, °R = ____________

Gas Analysis:

CO_2 Fraction, f_c = ____________
O_2 Fraction, f_o = ____________
Water Fraction, B_{ws} = ____________

Calibration Data:

Nozzle Diameter, d_n, in. = ____________
Pitot Coefficient, C_p = ____________
S_t = ____________
W_t = ____________

$M_d = 44(f_c) + 32(f_o) + 28(1 - f_c - f_o) =$ ____________________

$M_w = M_d\ (1 - B_{ws}) + 18(B_{ws}) =$ ____________________

$P_s = P_a + \frac{D_p \text{ Stack}}{13.6} =$ ____________________

$P_L = P_a + 0.59 =$ ____________________

$\mu_L = 51.05 + 0.207\ T_L + 3.2355 \times 10^{-5}\ T_L^2 + 53.147\ (f_o) =$ ____________________

$\mu_d = 51.05 + 0.207\ T_s + 3.2355 \times 10^{-5}\ T_s^2 + 53.147\ (f_o) =$ ________

Figure 15. EGR setup calculation worksheet II: total flow LFE ΔP (sheet 1 of 2).

EGR Worksheet II (Continued)

$$K_1 = 1.5752 \times 10^{-5} \; \frac{\mu_L T_L \, P_s^{0.7051} \; \mu_d}{P_L M_d^{0.2949}} = \underline{\hspace{5cm}}$$

$$K_2 = 0.1539 \; \frac{\mu_L T_L d_n^2 \; C_p}{P_L} \sqrt{P_s} = \underline{\hspace{5cm}}$$

$$K_3 = \frac{B_{ws}\mu_d \left[1 - 0.2949\left(1 - \frac{18}{M_d}\right)\right] + 74.143 \; B_{ws}(1 - B_{ws})}{\mu_d \; - \; 74.143 \; B_{ws}} = \underline{\hspace{5cm}}$$

$$A_t = \frac{K_1}{S_t \; (T_s)^{0.7051}} - \frac{\mu_L}{180.1} \; \frac{W_t}{S_t} = \underline{\hspace{4cm}}$$

$$B_t = \frac{K_3 K_2}{S_t \sqrt{M_w \; T_s}} = \underline{\hspace{3cm}}$$

$$\Delta P_t = A_t - B_t \sqrt{\Delta P_{vel}} = \underline{\hspace{3cm}}$$

Figure 15. EGR setup calculation worksheet II: total flow LFE ΔP (sheet 2 of 2).

EGR WORKSHEET III

RECYCLE FLOW LFE ΔP

Barometric Pressure, P_a, in. Hg = ____________

Stack Differential Pressure, D_p Stack, in. H_2O = ____________

Average Stack Temperature, T_s, °R = ____________

LFE Temperature, T_L, °R = ____________

Gas Analysis:

CO_2 Fraction, f_c = ____________
O_2 Fraction, f_o = ____________
Water Fraction, B_{ws} = ____________

Calibration Data:

Nozzle Diameter, d_n, in. = ____________
Pitot Coefficient, C_p = ____________
S_r = ____________
W_r = ____________

$M_d = 44(f_c) + 32(f_o) + 28(1 - f_c - f_o)$ = ____________

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = ____________

$P_s = P_a + \frac{D_p \text{ Stack}}{13.6}$ = ____________

$P_L = P_a + 0.59$ = ____________

$\mu_L = 51.05 + 0.207\ T_L + 3.2355 \times 10^{-5}\ T_L^2 + 53.147(f_o)$ = ____________

$\mu_d = 51.05 + 0.207\ T_s + 3.2355 \times 10^{-5}\ T_s^2 + 53.147(f_o)$ = ____________

$K_1 = 1.5752 \times 10^{-5}\ \frac{\mu_L T_L}{P_L}\ \frac{P_s^{0.7051}\ \mu_d}{M_d^{0.2949}}$ = ____________

$K_2 = 0.1539\ \frac{\mu_L\ T_L\ d_n^2\ C_p}{P_L} \sqrt{P_s}$ = ____________

Figure 16. EGR setup calculation worksheet III: recycle flow LFE ΔP (sheet 1 of 2).

EGR Worksheet III (Continued)

$$K_4 = M_w^{-0.2051} M_d^{-0.2949} \left(\frac{\mu_d}{\mu_d - 74.143 B_{ws}} \right) = \_\_\_\_\_\_\_\_\_\_$$

$$A_r = \frac{K_1}{S_r (T_s)^{0.7051}} - \frac{\mu_L}{180.1} \frac{W_r}{S_r} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_$$

$$B_r = \frac{K_4 K_2}{S_r \sqrt{T_s}} = \_\_\_\_\_\_\_\_\_\_$$

$$\Delta P_r = A_r - B_r \sqrt{\Delta P_{vel}} = \_\_\_\_\_\_\_\_\_\_\_\_$$

Figure 16. EGR setup calculation worksheet III: recycle flow LFE ΔP (sheet 2 of 2).

To obtain a function of this type for ΔH, ΔP_t or ΔP_r, stack temperature is assumed to be constant. Values for ΔH and ΔP_t obtained in this manner were found to agree with exact solutions to ±10% for temperature ranges of ±50 °F around the average and stack gas moisture up to 50%.

5.4. NOZZLE SELECTION

Selection of the appropriate nozzle size for EGR sampling is not as straightforward as in Method 5. For Method 5 sampling, the only consideration when choosing a nozzle size is that it must provide a flow rate of approximately 0.75 dscfm at isokinetic conditions. When sampling with the EGR system, the recycle rates anticipated at each traverse point must also be considered. The chosen nozzle should not require recycle rates less than 10% or greater than 80% of the total flow.

The first step in nozzle selection is to determine the PM_{10} flow rate for the sampler at the average stack temperature, pressure and moisture fraction. This flow rate has been defined previously as Q_w and may be calculated by using equation 5-10.

The target nozzle diameter may then be calculated as shown below:

$$d \text{ (inches)} = 1.74808 \sqrt{\frac{Q_w}{V_{max}}} \qquad (5\text{-}19)$$

Because periodic fluctuations in duct velocity can occur, the velocity used in the above calculation should be the maximum expected velocity increased by 10%.

Once the target nozzle diameter has been determined, the next smallest available nozzle size should be chosen for sampling. The actual, calibrated size of the chosen nozzle should be used for all setup calculations.

SECTION 6

TAKING THE SAMPLE

6.1. FIELD ASSEMBLY

After the EGR sampling system has arrived at the test site it should be visually inspected for any damage incurred during transport. To check for internal probe damage, a positive pressure leak check on each of the four lines running through the probe is recommended. This check is performed by blocking one end of each line and applying positive pressure at the other. The pressure on the line is monitored with a manometer connected in parallel. Failure to hold pressure indicates an internal probe leak, which should be found and repaired before proceeding.

When it has been determined the EGR system is in proper operating condition, the operator should begin assembling the system. The particle-sizing device should be assembled as its specific operating manual dictates. The EGR nozzle should then be attached to the sampler and the complete device mounted on the probe by using tube unions, as necessary, to attach the sampler to the sample line. The nozzle recycle line should be attached to the temperature-monitored recycle line on the probe. With flexible extension tubes of proper length, the pitot head should then be mounted on the probe. The EGR sampling nozzle and one leg of the pitot tube must face the same direction while all the tubing unions are fully tightened. A combined umbilical or individual tubing can then be used to connect the probe to the control console. If individual tubing is used, the recycle line should run directly from the probe to the control box. The sample line should be attached to the inlet of the water dropout system (condenser and silica gel column), which is, in turn, attached to the sample inlet of the control console. An umbilical that encloses the recycle line, the sample line, and the various thermocouple extensions in a single sheath is preferred if it is available.

Because the amount of water collected from the condensing system must be known, all components of this system should be clean and free of any foreign material. If silica gel columns are used, a preweight of the column and silica gel should be obtained before any testing. Then the column must be sealed until testing begins to avoid any accidental uptake of moisture. After sampling, the column should be weighed again to determine the amount of water uptake. If a condenser is used, it should be placed in an ice chest and ice added to the chest until the condenser is sufficiently covered.

After establishing power to the control console, the multipin, electrical thermocouple connector should be attached at both the probe and the control box. The readouts of the thermocouples should be checked before proceeding to ensure all are working properly. The manometer leads should be check to make sure they are connected to the correct port and that each port is in the open position. The pump should be connected to the EGR control box, with the hoses provided. The pump's power cord should be plugged into the control box near the pump flow lines. At this point the EGR sampling system is fully assembled and ready for a presampling leak check.

6.2. LEAK TEST

The sampler, probe, condenser, and sampling lines should be leak-checked before final assembly. This can be achieved by plugging one end of the line to be tested and applying a positive pressure at the opposite end. By placing a pressure gauge in parallel with the test line, the pressure within the system can be monitored. If the system fails to maintain pressure after it is sealed, a soap solution can be used to locate leaks.

When the system has been completely assembled, the EGR control console pump may be used to leak check the vacuum system as in Method 5 by following the procedure below.

- Plug the sampling nozzle
- Turn the recycle gas valves completely off, and turn on the EGR pump to produce a vacuum across the desired test section
- Use the total flow fine-adjust valve to set the system vacuum to 15 in. Hg.

If the required vacuum reading on the console-mounted vacuum gauge cannot be achieved or if the gas meter indicates a leak rate greater than 0.02 cfm, the system is not sealed and the leak(s) must be located and fixed.

The positive pressure portion of the control console can be tested for leaks by using the procedure described in Section 3. As an alternative, an auxiliary pump-DGM system (or spare sampling system) may be used to draw a vacuum in this portion of the system, as follows:

- Attach the recycle output of the EGR system, by using latex or similar tubing, to the inlet of the auxiliary system
- Completely open the recycle valves and close the total flow and sample back-pressure valves
- Continue the procedure as outlined in the preceding paragraph

The same leak-rate limit (<0.02 cfm) should be applied to the positive side of the system as is used for the negative side.

6.3. PRETEST EQUIPMENT WARM-UP

Because most flue streams to be tested are not at ambient temperatures, the EGR sampling train must be heated to stack conditions. This helps ensure isokinetic sampling, significantly reduces the chance of acid deposition within the sample line, and allows isothermal introduction of recycle gas at the inlet of the particle-sizing device. This is accomplished through the use of the heated EGR probe and in-the-flue heating of the sampler.

The sampler should be heated in the flue long enough to equilibrate with the temperature of the surrounding stack gasses. Typically, the PM_{10} sampler should remain in the flue at least 15-20 min. to ensure thermal equilibrium. The nozzle, if uncapped, should not point into the flow field during preheating. If possible, the nozzle should be capped or plugged during preheating, and the cap or plug removed immediately before sampling.

The probe temperature is regulated by a proportional temperature controller. While the sampling device is heating in the gas stream, the probe heater controller should be adjusted to heat the recycle line to stack temperature. When condensible vapors are present, the probe should be heated to and maintained above the dew point. Care should be taken to ensure that vapor does not condense in the portion of the probe extending outside the duct and flow back into the sampler.

6.4. FLOW RATES

As stated previously, the flow rate through the sampling nozzle is directly dependent on the stack gas velocity at the sample point. In operation, therefore, the pressure drop across the sample orifice, ΔH, is adjusted according to the previously determined run calculations with shifts in the pitot ΔP readings. This ensures continued isokinetic sampling. In turn, the flow rate of the recycle gas must also be adjusted to maintain the proper total flow through the particle-sizing device. During start-up the operator initially sets the total sampler flow rate by using valves V_1 and V_2. After setting the approximate total flow rate, the sample flow rate is set by adjusting the recycle valves V_3 and V_4. If high recycle ratios are required, the back-pressure valve, V_5, may need to be adjusted. Because there is some interaction between flow rates, a few minor repeat adjustments may be required between the total and sample flow rates. Typically, when traversing to another sampling point, only the fine recycle adjust (V_4) or the sample back-pressure valve (V_5) will need adjustment. These point-to-point adjustments may require slight adjustment to the total flow. If so, repeat the iterative process outlined above until the target ΔP_t and ΔH sample values are achieved. The practiced operator can usually obtain the target values within one or two iterations at each new point.

6.5. TRAVERSING

During traversing (moving to a new point or new port), all motion should be smooth and brief to avoid bumping or vibrating the sampler. When removing or inserting the sampler, care must be taken not to scrape the nozzle on the port wall. Also, the sampler should not be allowed to bump against the far inside wall of the duct.

6.6. FLOW RATE CHECKS

During sampling, a quality assurance check of the flow rates through the EGR system should be performed periodically to ensure proper operation. By definition, the total flow through the EGR sampling system is the sum of the recycle and sample gas flows. For example, if the total flow LFE reading relates to 1.0 cfm and the sample orifice pressure relates to 0.6 cfm, the reading on the recycle LFE must relate to 0.4 cfm. The EGR setup equations use this principle to calculate the orifice, total LFE, and recycle LFE settings for a given stack temperature and velocity ΔP. Therefore, when the total LFE and sample orifice pressure differentials have been set to the appropriate values, the recycle LFE reading from the control box should agree with the value provided by the setup calculations to ±10%.

If the flows are fairly constant, the EGR dry gas meter may also be used as a quality assurance check. By measuring the seconds per revolution of the gas meter rotation needle, the sample flow rate can be determined. This, by definition, is the difference between the total and recycle gas flow rates.

6.7. SHUTDOWN ORIENTATION

Depending on the orientation of the sampler, it may be advisable to maintain an appreciable flow rate while removing the sampler from the flue. Extreme care must be taken during removal so the sample is not contaminated by dust from the port walls. The flow rate should be maintained until the sampler can be placed in a favorable orientation (usually horizontal). This is particularly true when operating a cyclone in a vertical orientation. Otherwise, some dust might fall from one stage of the sampler to another and thus be measured where it was not collected. After the flow has been terminated, the sampler can be transported to the laboratory. It should be kept in a horizontal position with the nozzle plugged or covered to avoid contamination or loss of sample.

6.8. DATA LOGGING

The parameters of the test should be recorded in a clear, concise format like that shown in Figure 17. Parameters that are likely to change, such as sample and recycle gas flow rates, should be recorded periodically. Other examples are port number, traverse point, gas meter temperature, gas meter volume, metering orifice and LFE pressure drops, atmospheric pressure, stack gas temperature, etc.

Run Code	Date	Stack Temperature (°F)	Gas Composition %CO_2 %O_2 %CO
Sampler ID	Start Time	Differential Stack Pressure (in.H_2O)	Moisture Content
Filter ID	End Time	Ambient Temperature (°F)	
Sampler Orientation	Sampling Duration (min)	Ambient Pressure (in.Hg)	
Sampling Location	DGM (initial)	Gas Velocity	Pitot Leak Check (Pos) (Neg)
Nozzle Diameter-ID (in)	DGM (final)	System Leak Check	Notes
Operator(s)	Sample Volume (ft^3)		
Dual Manometer Leveled and Zeroed?			
Magnehelics Zeroed?			

Run Time	Port No Trav.Pt.	ΔP Pitot	ΔH Sample	DGM Volume	ΔP Total	P Inlet	ΔP Recycle	T_1 Stack	T_2 Recycle	T_3 Probe	T_4 LFE	T_3 DGM

6211-18

Figure 17. Suggested EGR run sheet.

SECTION 7

SAMPLE RETRIEVAL

After the sampling system has been allowed to cool to a point where it can be safely handled, the collected sample may be carefully recovered.

7.1. RECOVERY OF THE PARTICULATE MASS

Great care is needed during recovery of the collected particles from the PM_{10} sampler to ensure that all of the particulate matter is recovered and placed in the proper sample containers. The sample can be effectively recovered from both stages of the PM_{10} sampler (cyclone and filter) by using a combination of brushing and washing.

The first step in recovery of the particulate matter from the nozzle and cyclone is brushing the collected mass into the appropriate foil envelope. A clean no. 7 camel's hair brush or small nylon bristle brush is suggested for this operation. The brushed surfaces should then be rinsed thoroughly with acetone, or similar solvent, to recover any particles that continue to adhere to the sampler. These rinses should be collected in a uniquely identified sample container. The brush used for recovery should also be rinsed into this container.

The filter should be recovered from the filter holder and returned to the appropriate container. Any particulate matter or filter fibers adhering to the filter holder surfaces or rubber O-ring should be brushed onto the surface of the filter. The interior surfaces of the filter holder should then be rinsed with the solvent as described above.

As stated previously, assignment of the collected particulate matter to the appropriate sample container is very important. Particulate matter collected from the inner surfaces of the EGR nozzle, the cyclone body, collection cup and cap are to be considered as collected by the cyclone. Furthermore, any matter brushed or rinsed from the outside of the cyclone exit tube is also to be considered part of the cyclone catch. The PM_{10} fraction consists of particulate matter collected from the inner surface of the "turnaround" on the cyclone cap, the inside wall of the exit tube, the inner walls of the filter holder (upstream of the filter), and the surface of the filter.

Final weights for all particulate samples should be determined on site, prior to shipment. Recommended procedures are outlined in Section 8.

7.2. MOISTURE DETERMINATION

The condenser should be drained of any collected moisture and the amount of liquid determined either volumetrically (to ± 1 mL) or gravimetrically (to ±0.5 g). The liquid may be discarded after the weight or volume is recorded. The spent silica gel should be weighed in the appropriate container (such as the drying column or shipment container) to determine the moisture uptake.

SECTION 8

POSTSAMPLING CHECKS

Posttest activities for the EGR system involve equipment calibration checks, field sample analysis, and equipment maintenance. The first two items will be discussed in this section. The third item is discussed in Section 10 of this manual.

8.1. EQUIPMENT CALIBRATION CHECKS

A posttest calibration check of the flow metering devices is required. The posttest calibration checks should be performed as described in Section 3 of this manual. If the gas meter correction factor obtained from the calibration check deviates from the initial calibration factor by more than 5%, the meter should be recalibrated. The posttest data reduction should then be performed with whichever calibration factor yields the lower gas meter volumes. If the calibration check of the total flow LFE deviates from the initial calibration by more than 10%, the LFE should also be recalibrated. The calibration factor used for data reduction should be that which yields the higher cyclone flow rate.

Calibration checks should also be performed on the stack, dry gas meter, and LFE thermocouples. Each of the above temperature sensors should be compared with a mercury-in-glass thermometer at ambient temperature. If the stack temperature thermocouple reading differs from the reference by more than 1.5% of the absolute temperature, the thermocouple should be recalibrated as described in Section 3. The old and new calibrations should be compared to determine the sign and magnitude of the correction to be applied to the average stack temperature. If the DGM or LFE thermocouple readings vary from the reference by more than 6 °C (10.8 °F), the thermocouples should be recalibrated. For data reduction calculations, the calibrations that give the higher DGM or LFE temperatures should be used.

A posttest calibration check is also required for the system magnehelic gauges. This calibration check should be performed as described in Section 3.

8.2. SAMPLE ANALYSIS

Analysis of the EGR field samples is essentially the same as for Method 5. Filter and cyclone catches should desiccate for a minimum of 24 h before the initial weighing. Each sample should be weighed to a constant weight, which is achieved when the difference between consecutive weighings is no more than 0.5 mg or 1% of the total weight less tare weight, whichever is greater; no less than 6 h of desiccation time should be allowed between weighings.

As an alternative, the samples may be oven dried at the average stack temperature or 220 °F, whichever is less, for 2 to 3 h, cooled in a desiccator, and weighed to a constant weight. The tester may also opt to oven dry the samples as described above, weigh the sample, and use this as the final weight. Whichever option is chosen, final weights of all cyclone and filter samples should be determined to the nearest 0.1 mg on site, before shipping.

Acetone rinse and blank samples should be inspected to confirm that no leakage has occurred. If a noticeable amount of sample has been lost through leakage, the sample must either be declared void or corrected in the final results with methods approved by the sponsoring agency. The liquid should be measured either volumetrically to ±1 mL or gravimetrically to ±0.5 g. Each sample should be evaporated to dryness at ambient temperature and pressure in a tared 250-mL beaker or similar container. The evaporated samples should be desiccated for 24 h and weighed to a constant weight. Results should be recorded to the nearest 0.1 mg.

If the silica gel was not analyzed in the field, the spent silica gel samples should be weighed in the appropriate container to the nearest 0.5 g.

SECTION 9

DATA ANALYSIS

9.1. AVERAGE RUN PARAMETERS

To calculate the resultant values from a test run, the average values of the recorded temperatures and pressure drops must be calculated. The pressure drop across the pitot tube, however, requires special attention. The stack velocity is a function of the square root of the pitot ΔP; therefore, a straight average of the ΔPs over a given run would not result in the true average velocity. Because of this, the value used for calculating the average velocity must be the average square root of the velocity heads $\left[(\sqrt{\Delta P_{vel}})_{avg} \right]$. This will result in a ΔP_{vel} value that allows calculation of the true average velocity.

9.2. DRY GAS (SAMPLE) VOLUME

The sample volume measured by the EGR dry gas meter can be corrected to standard conditions (68 °F, 29.92 in. Hg) by using the following equation:

$$V_{MS} = (V_M \gamma) \left(\frac{T_{ST}}{T_M}\right) \left(\frac{P_a + \frac{\Delta H}{13.6}}{P_{ST}}\right)$$

$$= 17.65 \, (V_M \gamma) \left(\frac{P_a + \frac{\Delta H}{13.6}}{T_M}\right) \qquad (9\text{-}1)$$

9.3. SAMPLE FLOW RATE

The sample flow rate at standard conditions can be found by using equation 9-2

$$Q_{s_{ST}} = \frac{V_{MS}}{\theta} \qquad (9\text{-}2)$$

9.4. RECYCLE AND TOTAL GAS FLOW RATES

The recycle and total gas flow rates are monitored by LFEs. Therefore, the average flow rates through these devices (Q_r and Q_t, respectively) can be determined by using the manufacturers calibration charts or an empirically determined calibration equation in the form shown below.

$$Q_{t_{ST}} = \left(S_t \Delta P_t \left(\frac{\mu_{ST}}{\mu_L}\right) + W_t\right)\left(\frac{T_{ST}}{T_L}\right)\left(\frac{P_L}{P_{ST}}\right)$$

$$= 17.65 \left(S_t \Delta P_t \left(\frac{180.1}{\mu_L}\right) + W_t\right)\left(\frac{P_L}{T_M}\right) \qquad (9\text{-}3)$$

$$Q_{r_{ST}} = \left[S_r \Delta P_r \left(\frac{\mu_{ST}}{\mu_L}\right) + W_r\right]\left[\frac{T_{ST}}{T_L}\right]\left[\frac{P_L}{P_{ST}}\right]$$

$$= 17.65 \left[S_r \Delta P_r \left(\frac{180.1}{\mu_L}\right) + W_r\right]\left[\frac{P_L}{T_L}\right] \qquad (9\text{-}4)$$

9.5. VOLUME OF WATER VAPOR

The volume of the water vapor collected from flue gas is calculated as follows:

$$V_{WS} = V_{\ell c} \left(\frac{\rho_{H_2O}}{M_{H_2O}}\right) \left(\frac{R_u T_{ST}}{P_{ST}}\right]$$

$$= 0.04707 \; V_{\ell c} \qquad (9\text{-}5)$$

9.6. MOISTURE CONTENT

The moisture content of the stack (or sample) gas is calculated by the equation

$$B_{ws} = \frac{V_{WS}}{V_{MS} + V_{WS}} \qquad (9\text{-}6)$$

The addition of a known amount of dried recycle gas to the measured sample gas upstream of the particle-sizing device changes the moisture content of the gas mixture. This new moisture content is determined by the equation below.

$$B_{mix} = \left(\frac{Q_S}{Q_t}\right) B_{ws} \qquad (9\text{-}7)$$

Because of the difference in the moisture content of the stack gas and the mixed gas in the cyclone, the wet molecular weight of the two gases will also be different. The wet molecular weight of both gases may be calculated from equation 5-2 using the appropriate moisture fraction (e.g. use B_{mix} to determine the wet molecular weight of the mixed gas, M_{wm}).

9.7. FLOW RATES (ACTUAL CONDITIONS)

To calculate the particle cut diameter of the inertial classifier, it is necessary to know the flow rate through the sampler at the actual sampler conditions. This can be accomplished by using the following equation:

$$Q_t = Q_{t_{ST}} \left(\frac{1}{1 - B_{mix}}\right) \left(\frac{T_s}{T_{ST}}\right) \left(\frac{P_{ST}}{P_s}\right)$$

$$= 0.056\ Q_{t_{ST}} \left(\frac{1}{1 - B_{mix}}\right) \left(\frac{T_s}{P_s}\right) \qquad (9\text{-}8)$$

It is also necessary to calculate the sample and recycle flow rates and express them in terms of stack conditions. The format shown in equation 9-8 should be used for these calculations. However, for the sample flow rate the moisture fraction becomes the actual stack moisture content, B_{ws}, and for the recycle flow rate the moisture content equals zero.

9.8. RECYCLE RATIO

The actual recycle ratio through the cyclone sampler may be calculated by the equation

$$PR = \left(\frac{Q_t - Q_s}{Q_t}\right) \times 100\% \qquad (9\text{-}9)$$

9.9. STACK GAS VELOCITY

The average stack gas velocity or the gas velocity at any one point within the stack can be found by using the following equation:

$$V_s = K_p C_p \left(\sqrt{\Delta P_{vel}}\right)_{avg} \left(\frac{T_s}{P_s M_w}\right)^{1/2} \qquad (9\text{-}10)$$

K_p = 85.48 ft/s (lb/mole-°R) when these units are used

9.10. CONCENTRATION

The concentration of the particulate matter caught by each stage and the total particulate concentration in the stack gas can be calculated by the equation below:

$$C'_m = 0.0154 \text{ gr/mg} \left(\frac{M_p}{V_{MS}}\right) \qquad (9\text{-}11)$$

where C'_m = concentration of particulate matter for a given stage or in-stack gas, grains per dry standard cubic foot (gr/dscf),

M_p = mass of collected particulate (either per stage or total), mg

The units of gr/scf can be converted to milligrams per dry normal cubic meter, mg/dNm^3, by using the following:

$$C_m = 2293.2\ C'_m \qquad (9\text{-}12)$$

9.11. SAMPLER D_{50}

The D_{50} or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flow rate through the sampler and the viscosity and density of the gas mixture. The procedure for calculating the actual flow rate (acfm) was described previously. The viscosity of the mixture must be calculated. As was shown in equation 5-3, it can be determined as follows (Williamson et al., 1983):

$$\mu_m = C_1 + C_2T + C_3T^2 + C_4B_{mix} + C_5f_O \qquad (9\text{-}13)$$

where μ is in micropoise, T in °C, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

for T in °R

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147.$

The currently available data concerning calibration of Cyclone I, used to obtain the 10-μm cut for PM_{10} measurement, show the behavior to be described by the equation

$$D_{50} = 0.15625 \left(\frac{M_{wm} P_s}{T_s}\right)^{-0.2091} Q_t^{-0.7091} \mu_m^{0.7091} \qquad (9\text{-}14)$$

Because the proposed PM_{10} cyclone is actually part of a five-stage series cyclone system, it may at some point be desirable to operate the full cyclone set with the EGR system. If such is the case, the D_{50}'s for each of the remaining cyclones should be calculated as described in the vendor-supplied operator's manual.

9.12. PERCENT ISOKINETIC

To ensure nonbiased particulate sampling, the following equation should be used to determine the percentage of isokinetic sampling:

$$I\% = \frac{1.677\ T_s \left[0.00267\ V_{\ell c} + \frac{V_M \gamma}{T_M}\left(P_a + \frac{\Delta H}{13.6}\right)\right]}{\theta\ V_s\ P_s\ A_n} \qquad (9\text{-}15)$$

If $90\% < I\% < 110\%$, the results are acceptable; otherwise, reject the results and repeat the test.

SECTION 10

MAINTENANCE

A notebook or other record of all maintenance procedures should be kept. This will provide a definite and current record of all information pertinent to reliable operation of the EGR sampling system. Maintenance of the system should be performed as described previously (Rom, 1972) with the exceptions noted below.

10.1. VACUUM SYSTEM

A preventative maintenance check of the vacuum system is performed as follows:

- Insert a plugged 1/2-in. male quick-connect into the sample inlet of the EGR control console.
- Turn the pump switch to ON.
- Turn the coarse-adjust valve to the ON position.
- Close fully the fine-adjust valve and the recycle valves.

The vacuum gauge should read about 25 in. Hg when ambient barometric pressure is near 30 in. Hg. If this pressure cannot be achieved, a leak or sticking pump vane should be suspected. If the leak rate measured by the dry gas meter exceeds 0.02 cfm, the leak or leaks must be found and corrected. Parts to check are the pump, vacuum gauge, metering valves, and tubing.

10.2. EGR PUMP

Because the gas recirculated within the EGR system must be free of any foreign particles or vapors, the system is equipped with a leak-free, carbon-vane pump. The pump requires no lubrication, and little maintenance is needed to ensure long working life. The most important factor in ensuring long pump life is to allow only clean, dry gas to circulate through the pump. This is accomplished through the sampling system backup filter and condenser. Unlike the oil-lubricated pumps used in most commercial Method 5 control boxes, this pump should never be operated with oil in the muffler jars.

During start-up if the motor fails to start or hums, the operator should pull the plug and check for the correct current. It should be 5 to 6 A. The operator should also visually inspect the plug and switch. If the unit is extremely cold, it may be helpful to bring the unit to room temperature before starting.

Most pump trouble can be corrected by flushing the unit according to the manufacturer's instructions rather than disassembly. A noisy or inefficient pump is frequently caused by nothing more serious than a vane stuck in a rotor slot because of foreign material in the unit. To flush the unit, follow the procedure given below.

- Separate the pump from the system.
- Slowly add several teaspoons of solvent at the intake while the unit is running (recommended commercial solvents include Loctite Safety Solvent, Inhibisol Safety Solvent, or Dow Chemical Chlorothane).
- Lay the unit on its side with the outlet downward so the solvent will work out again.

If flushing does not eliminate the problem, take the corrective actions below:

- Remove only the end plate and the four carbon vanes.
- Remove any visible foreign materials, and clean the chamber with solvent.
- Use the solvent to clean any buildup on inner pump walls, which is caused by normal wear of the carbon vanes.

- Replace any broken or excessively worn vanes.
- Replace the pump end plate.
- Check the unit for leaks by plugging the inlet of the pump and connecting a gas meter to the outlet.

If the pump causes the gas meter to register a reading, the pump end plate should be retightened and leak-checked again. This should be repeated until the unit is leak-free.

10.3. MAGNEHELIC DIFFERENTIAL PRESSURE GAUGES

Magnehelic differential pressure gauges are precision instruments assembled and precalibrated by the manufacturer. If trained instrument mechanics are not available, it is recommended that any instruments requiring repair be returned to the factory.

No lubrication or periodic servicing is required. If the interior is protected from dust, dirt, and corrosive gases and fluids, years of trouble-free service may be expected.

10.3.1. Zero Adjustment

The indicating pointer should be set exactly on the zero mark by using the external zero-adjust screw on the cover at the bottom. The zero check or adjustment can be made only if the high and low pressure taps are both open to atmosphere.

10.3.2. Calibration Check

For service requiring a high degree of continued accuracy, periodic calibration checks are recommended. In general, the Magnehelic calibration should be checked, along with the LFEs, by following the procedure below.

1. As a comparison gauge, use a hook gauge, micromanometer, or inclined gauge of known accuracy.

2. Connect the Magnehelic gauge and test gauge together with two leads from a "T." Connect rubber tubing to the third leg of the "T" and impose the pressure, slowly.

3. Be certain no leaks exist in the system, and provide adequate time for comparison gauges to reach equilibrium, because fluid drainage and different dynamic characteristics can affect the reading.

10.3.3. Recalibration

1. Remove plastic cover.

2. Remove two screws holding scale, and slide scale out, using care not to damage pointer.

3. Loosen two set screws in range spring clamp (Dwyer part no. NUA-70B); move toward the helix to increase the range and back to decrease. Secure the clamp with the set screws, replace scale, check zero, and compare reading as in preceding paragraph.

4. Replace cover. The cover must be tight and leakproof for accurate readings on high-pressure side. Observe the following procedure.
    a. Place the cover in position with notch engaged and with O-ring properly seated.
    b. Jockey zero-adjust screw into position so its hex end is inserted in the socket set screw, which actuates the zero-adjusting mechanism.
    c. Hold cover in position and screw bezel down snug. The O-ring must take some squeeze to effect an airtight seal.
    Caution: If bezel binds because of galling action of aluminum sur faces, lubricate sparingly with light oil or molybdenum sulfate com pound.
    d. Troubleshooting.
        1) Gauge sluggish.

- Leads may be plugged or leaking.
- Cover may be loose or leaking.
- Pointer may be touching scale.
- Jewels supporting helix may be overtightened.

2) Gauge fails to indicate zero properly.
   - See comments above regarding sluggish readings.
   - Iron particles in a strong magnetic field between helix and magnet. If found, they may be removed by touching each particle and withdrawing it with a small screw driver.
   - Magnet shifted and touching helix.
3) Apparent inaccuracy.
   - See preceding comments.
   - Improper connections to pick up desired differential.
4) Consult factory for unusual conditions of temperature, pressure, etc., and the effect on gauge operation and accuracy.

10.4. DUAL MANOMETER

A preventative maintenance check of the dual manometer is performed as follows:

- Visually check the pitot and orifice manometer lines to ensure they are free of fluid.
- Check for leaks, especially around the fluid-level zeroing controls and drain screws.
- Wipe the dual manometer clean. The back can be cleaned with compressed air, or the device can be removed from the control panel and wiped clean.
- If the dual manometer is unusually dirty, clean as recommended on the instruction plate.
- Make sure that the manometer ports are open (1 1/2 turns counterclockwise from the seat) and the manometer lines are connected.
- Level the manometer and check the fluid level.

- To fill the manometer with fluid, remove the screw on the left side. When the oil meniscus and the reflected image at zero are aligned, the fluid-level plunger (zeroing control) should have about 1/4 to 1/2 in. travel inward.

Note: During rough shipment, the manometer lines should be disconnected and the manometer ports closed by turning clockwise until sealed.

- If for any reason the manometer unit has been inverted, be sure the floating check valves of the manometer have returned to their normal position. These floating valves are located under the manometer ports and must be in the normal position to use the manometer.

10.5. PITOT TUBE

The pitot tube should occasionally be inspected for any deformation of the pressure inlets, because this may change the pitot calibration coefficient. Any dents or nicks should be repaired or the pitot head should be replaced if the damage warrants it. Before each test run, the operator should blow gently into each pitot inlet to check for obstructions. If the pitot tubes are clear, the pitot tube gauge will respond. If no response is noted, the operator should blow out the pitot lines with compressed air. The pitot can be checked for leaks by plugging one end of the tube and applying a positive pressure at the opposite end. If the tube will not maintain pressure, a soap solution can be used to identify the location of any leaks.

10.6. NOZZLES

The EGR nozzle should be visually inspected before any testing. If repair is necessary, a plumb bob should be used for inside damage or emery paper for outside damage. After any nozzle repair, the nozzle diameter should be remeasured. The knife edge of the nozzle should be covered with serum caps or similar covers to avoid damage when the nozzle is not in use.

10.7. THERMOCOUPLES

The thermocouples throughout the EGR system should occasionally be checked against room temperature by using a mercury-in-glass thermometer as the standard. If any thermocouples do not read within ±5 °C, the thermocouples or readout should be replaced or recalibrated.

10.8. EGR SAMPLING PROBE

10.8.1. Probe Cleaning

Before each field test, all lines of the EGR heated sampling probe should be cleaned. This includes the sample, recycle, and pitot tube lines. A probe-cleaning procedure is outlined below.

- Clean the probe internally by rinsing, first with tap water, then distilled, deionized water, followed by an acetone or dichloromethane rinse.
- Rinse the internal tubes with the chosen organic solvent and allow them to air dry.
- Visually inspect the probe for cleanliness, and repeat the procedure if necessary.
- Rinse the recycle line, even if it appears clean.
- Rinse the pitot lines with water and blow them out with compressed air.
- Clean the tube fittings associated with the EGR probe sample lines by brushing, rinsing with distilled, deionized water and then with acetone or dichloromethane; allow to air dry.
- Cover all open ends of the probe with serum caps or Saran Wrap when not in use to prevent them from becoming contaminated.

10.8.2. Probe Heater Check

The procedure below may be used to check the probe heater.

- Plug the probe heater line and controlling thermocouple into the control case, and turn the heater controller on to approximately 300 °F.
- The indicator light on the controller should come on, and the probe should become warm to the touch in a few minutes. After a few minutes, the indicator light should begin to cycle on and off.
- If the probe does not heat, check the probe for loose connections.
- If the probe still does not heat, it may be necessary to remove the probe lines from the probe sheath for inspection of the heating element, as follows:
    Remove the three set screws and tube fittings at the outlet end of the probe,
    Unscrew the front end connector and gently slide out the probe lines,
    Unwrap the insulation
    Visually inspect the probe heating element for shorts or burned spots, and
    If necessary, use an ohmmeter to measure the resistance between leads (approximately 17 ohms) and also to ground (infinite). Deviations from these values indicate faulty wiring.
- After any electrical problem has been solved, rewrap the probe lines with insulating material, and reassemble the probe.

10.9. CONDENSING SYSTEM

Because it is generally preferable to operate the EGR system with a Method 17 rather than Method 5 filter configuration, a condenser and silica gel column may replace the built-in impinger train assembly. An impinger system will be required if the "back-half" catch is to be measured. Whichever system is used for collection of water vapor from the sampled stack gas, it must be clean and free of leaks before being used. Glass impingers should be cleaned with distilled, deionized water and then acetone and should then be allowed to air dry. Stainless steel condensers should also be rinsed by the same procedure and allowed to air dry, inverted to ensure total drainage. The drying can be speeded by blowing out the condenser with compressed air. Silica gel columns (along with condensers) should be leak tested, along with the control box or separately, by applying positive pressure at the inlet and plugging the outlet. Ideally, these devices should maintain a pressure of at least 10 in. Hg above absolute. It is recommended new silica gel be used for each field test.

SECTION 11

AUDITING PROCEDURES

Routine quality assurance activities, such as equipment calibrations, are essential to obtaining good data. An assessment of the quality of these data may be made through an audit. The audit must be performed by using equipment or standards independent of those used in a measurement program to ensure that the tasks involved are being performed properly.

The audits recommended for use in a program using the EGR sampling system are similar to those described for Method 5 (U.S. Environmental Protection Agency, 1977). Two types of audits, performance and system, are commonly performed.

Performance audits provide a quantitative evaluation of the quality of data produced by a measurement system. One type of performance audit recommended for Method 5 assesses the accuracy of the system's flow metering devices using a critical flow orifice. This is also recommended for measurement programs using the EGR system. All four flow metering devices in the EGR system may be included in the audit by using the procedure for posttest calibration checks outlined in Section 3 of this report.

A performance audit of data processing is also recommended. As for Method 5, an audit of this type can uncover and eliminate errors in data transfer, calculations, etc. The flow of data from field data forms and weight sheets to data reduction programs or hand calculations should be traced for at least a portion of the data base. Calculation of results for a standard data set is another method by which data reduction procedures may be audited.

A system audit is a qualitative inspection and examination of the procedures and techniques used by the field team. This type of audit is strongly recommended if the team is not familiar with the EGR system.

SECTION 12

RECOMMENDED STANDARDS FOR ESTABLISHING TRACEABILITY

Although the use of quality control checks and independent audits is essential to obtaining data of the desired quality, another important consideration is the traceability of individual elements of the measurement process. All materials, equipment, and procedures used should be traceable to a standard of reference.

Working calibration standards should be traceable to primary or higher level standards. The EGR flow metering devices should be calibrated against a wet test meter that has been verified as required for Method 5. The performance of the analytical balance should be checked against Class-S weights that are traceable to NBS standards.

REFERENCES

Farthing, W. E. and A. D. Williamson. "A Unified View of Inertial Impactors and Cyclones." Presented at 1985 Annual Meeting of American Association for Aerosol Research, Albuquerque, NM, 1985.

Harris, D. B. and L. Beddingfield. "Isokinetic Sampling with Fixed Flow Rate Devices Using Exhaust Gas Recirculation." Presented at the Third EPA Symposium on Advances in Particle Sampling and Measurements, Daytona Beach, FL, 1981.

Martin, R. M. Construction Details of Isokinetic Source-Sampling Equipment. APTD-0581, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1971.

Rom, J. J. Maintenance, Calibration, and Operation of Isokinetic Source Sampling Equipment. APTD-0576, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1972.

Smith, W. B., D. B. Harris, and R. R. Wilson, Jr. A Five-Stage Cyclone System for In Situ Sampling. Environ. Sci. Technol. 13(11):1387-1392, 1979.

U.S. Environmental Protection Agency. Methods 1-5 of 40 CFR, Part 60, Appendix A.

U.S. Environmental Protection Agency. Quality Assurance Handbook for Air Pollution Measurement Systems, Volume III: Stationary Source Specific Methods, Section 3.4.8. EPA-600/2-77-026, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1977.

Wilke, C. R. A Viscosity Equation for Gas Mixtures. J. Chem. Phys. 8:517, 1950.

Williamson, A. D., D. L. Iozia, P.V. Bush, W. E. Farthing, J. D. McCain, and W. B. Smith. Development, Application, and Support of Particulate Sampling Procedures. 3rd Annual Report (1982). SRI-EAS-83-348, Southern Research Institute, Birmingham, AL, 1983.

Williamson, A. D., R. S. Martin, D. B. Harris, and T. E. Ward. "Design and Characterization of an Isokinetic Sampling Train for Particle Size Measurements Using Exhaust Gas Recirculation." Paper 84-56.5. Presented at the 77th Annual Meeting of the Air Pollution Control Association, San Francisco, CA, 1984.

APPENDIX A

EGR SYSTEM COMPONENTS

TUBE/PIPE FITTINGS

1/2-in. tube bulkhead quick-connect, S.S. (1 each)
1/2-in. tube quick-connect stem, S.S. (2 each)
1/2-in. tube quick-connect body, S.S. (1 each)
1/2-in. tube full flow quick-connect stem, S.S. (2 each)
1/2-in. tube full flow quick-connect body, S.S. (2 each)
3/8-in. tube bulkhead quick-connect, S.S. (1 each)
3/8-in. tube quick-connect stem, S.S. (2 each)
3/8-in. tube quick-connect body, S.S. (1 each)
1/4-in. tube bulkhead quick-connect, S.S. (2 each)
1/4-in. tube quick-connect stem, S.S. (4 each)
1/4-in. tube quick-connect body, S.S. (2 each)

5/8-in. tube union, S.S. (1 each)
1/4-in. tube union, S.S. (2 each)
1/4-in. tube bulkhead union, brass (6 each)
5/8-in. tube x 1/2-tube reducing union, S.S. (1 each)
1/2-in. tube x 3/8-tube reducing union, S.S. (1 each)
1/2-in. tube elbow, S.S. (1 each)
1/2-in. tube elbow, brass (3 each)
3/8-in. tube elbow, S.S. (1 each)
3/8-in. tube elbow, brass (1 each)
1/4-in. tube elbow, S.S. (2 each)
1/2-in. tube x 1/4-tube tube end reducer, brass (3 each)
3/8-in. tube x 1/4-tube tube end reducer, S.S. (1 each)

1/2-in. tube tee, brass (1 each)
3/8-in. tube tee, brass (1 each)
1/4-in. tube tee, S.S. (1 each)

5/8-in. tubing ferrules, Teflon (2 each)
1/2-in. tubing ferrules, Teflon (2 each)
3/8-in. tubing ferrules, Teflon (2 each)
1/4-in. tubing ferrules, Teflon (4 each)

1/2-in. tube x 1/2-NPT male connector, brass (1 each)
1/2-in. tube x 3/8-NPT male connector, brass (2 each)
1/2-in. tube x 1/4-NPT male connector, S.S. (1 each)
1/2-in. tube x 1/4-NPT male connector, brass (2 each)
3/8-in. tube x 1/4-NPT male connector, brass (1 each)
1/4-in. tube x 1/8-NPT male connector, S.S. (4 each)
1/2-in. tube x 1/4-NPT female connector, brass (2 each)
3/8-in. tube x 1/4-NPT female connector, brass (3 each)
1/4-in. tube x 1/4-NPT female connector, brass (1 each)
5/8-in. tube x 1/2-NPT male elbow, brass (1 each)
1/2-in. tube x 1/2-NPT male elbow, brass (2 each)
1/2-in. tube x 1/4-NPT male elbow, brass (1 each)
3/8-in. tube x 1/2-NPT male elbow, brass (1 each)
3/8-in. tube x 1/4-NPT male elbow, brass (1 each)
1/4-in. tube x 1/8-NPT male elbow, brass (12 each)
1/2-in. tube x 1/2-NPT male branch tee, brass (1 each)
1/2-in. tube x 3/8-NPT male run tee, brass (1 each)

1/4-in. tube x 1/4-hose hose/tube adapter, brass (26 each)

3/8-NPT x 1/4-NPT reducing adapter, S.S. (1 each)
3/8-NPT x 1/4-NPT bushing, brass (1 each)
3/8-NPT coupling, brass (1 each)
1/4-NPT adapter, brass (1 each)
1/4-NPT male tee, brass (3 each)

3/8-NPT x 1/2 hose barb connectors, nylon (1 each)
3/8-NPT x 1/2 hose barb elbow, nylon (1 each)
1/4-NPT x 1/4 hose barb connector, S.S. (4 each)
1/8-NPT x 1/4 hose barb connector, brass (6 each)

1/4 hose barb tee, nylon (10-15 each)

1/4 flexible metal hose connector, S.S. (1 each)
    -Swagelok #SS-4HO-6-S4; short length

0.281-orifice ball valve, S.S. (2 each)
    - Whitey #SS-44F4
0.250-orifice angled regulating valve, S.S. (3 each)
    - Whitey #SS-1RF4-A
0.125-orifice 3-way ball valve, brass (6 each)
    - Whitey #B-42XF2

COPPER SWEAT FITTINGS

1/2-inch elbow (8 each)
3/8-inch elbow (4 each)
1/4-inch elbow (1 each)
1/2-inch tee (1 each)

FLOW (or VOLUME) MEASUREMENT

Laminar flow element, total flow (1 each)
- Meriam 50MJ10-10

Laminar flow element, recycle flow (1 each)
- Meriam 50MJ10-11

Dry gas meter, sample volume (1 each)
- Rockwell T-100 series (thru Andersen Samplers, Inc.)

PRESSURE MEASUREMENT

0 - 4 inWG magnehelic, (1 each)
- Dwyer #2004

0 - 8 inWG magnehelic, (1 each)
- Dwyer #2008

0 - 25 inWG magnehelic, (1 each)
- Dwyer #2025

Vacuum gauge, panel mount (1 each)
- Omega #PGP-25 B-30V

0 - 10 inWG dual inclined-vertical manometer (1 each)
- Dwyer #422-10

TEMPERATURE MEASUREMENT

Temperature controller (1 each)
- Omega Model 6100 (#6102-K-0/500 °F)

Thermocouple, type K, Readout (1 each)
- Omega Model 199A (#199KF) (may substitute Model 115)

10-position thermocouple switch (1 each)
- Omega #OSW3-10

Flanged female multipin connector, 24 position (1 each)
- Omega #MTC-24-FF

Male multipin connector, 24 position (1 each)
- Omega #MTC-24-MC

Male multipin connector, 12 position (1 each)
- Omega #MTC-12-MC

Female multipin connector, 12 position (1 each)
- Omega #MTC-12-FC

Backshell cable clamp, for 24 position connector (1 each)
- Omega #MTC-24-SHL

Backshell cable clamp, for 12 position connector (2 each)
- Omega #MTC-12-SHL

Alumel sockets (6 each)
- Omega #MTC-AL-S

Alumel pins (6 each)
- Omega #MTC-AL-P

Chromel sockets (6 each)
- Omega #MTC-CH-S

Chromel pins (6 each)
- Omega #MTC-CH-P

Gold-plated sockets (12 each)
- Omega #MTC-Au-S

Gold-plated pins (12 each)
- Omega #MTC-Au-p

Sealing plugs (12 each)
- Omega #MTC-HP

Type K thermocouple, open bead, 1/4" dia x 4" L (2 each)
- Omega #CASS-14E-4

Type K T.C. ext wire, 20 AWG, stranded, polyvinyl insl (100 ft)
- Omega #EXPP-K-20S

Type K T.C. ext wire, 24 AWG, solid, glass insl (15 ft)
- Omega #GG-K-24

Type K T.C. ext wire, 24 AWG, glass insl & SS overbraid (30 ft)
- Marlin Man. Corp. #628S-K-24-30 ft

Hi-temp mini plugs, Type K (2 each)

Type K T.C. ext wire, 24 AWG, solid, glass insl (15 ft)
- Omega #GG-K-24

Type K T.C. ext wire, 24 AWG, glass insl & SS overbraid (30 ft)
  - Marlin Man. Corp. #628S-K-24-30 ft
Hi-temp mini plugs, type K (2 each)
  - Marlin Man. Corp. #H-1260-K
Hi-temp mini jacks, type K (2 each)
  - Marlin Man. Corp. #H-1210-K
Mini cable clamps (4 each)
  - Marlin Man. Corp. #1280
Female thermocouple connectors, type K (4 each)
  - Omega #OST-K-F
Panel adapters, round hole (2 each)
  - Omega #RSACL

ELECTRICAL COMPONENTS

Toggle switch, DPDT, On-On, rated 15 amps at 120 VAC (2 each)
  - Newark Electronics Type 7565K5
Toggle swith, DPDT, On-Off, rated 15 amps at 120 VAC (2 each)
  - Newark Electronics Type 7561K4
Green modular panel lights, 120 VAC & 1.5 mA, w/bushing (5 each)
  - Newark Electronics Type G5115 (bushing Type 100-G)
Red modular panel lights, 120 VAC & 1.5 mA, w/bushing (2 each)
  - Newark Electronics Type N5115 (bushing Type 100-R)
Circuit breaker, two-pole, 25 amps, Potter & Brumfield (1 each)
  - Newark Electronics #W92X11-2-25
Male plug, 120 VAC & 15-20 amps (2 each)
Female recepticles, recessed, 120 VAC & 15-20 amps (2 each)
Male plug, recessed, "twist-lock", 120 VAC & 20 amps (1 each)
Female recepticle, "twist-lock", 120 VAC & 20 amps (1 each)
Power cord, 3-wire, 12-14 gage (30 ft each)
Power cord, 2-wire, 14-16 gage (40 ft each)
Electrical wire, 14-16 gage, stranded, black sheath (30 ft each)

Electrical wire, 14-16 gage, stranded, white sheath (30 ft each)
Electrical wire, 14-16 gage, stranded, green sheath (60 ft each)
Terminal block, 15-20 position w/jumpers (1 each)
Heat shrink tubing, black, 3/16-1/8 dia (3 ft each)
Heat shrink tubing, white, 3/16-1/8 dia (3 ft each)
Assortment electrical connectors, ring and forked
Assortment wire nuts
Assortment cable tie mounts, self-sticking
Assortment wire ties, nylon, 3-inch length
2-way solenoid, miniature, 120 VAC - 16.7 watts (2 each)
    - ASCO #8262A152
3-way solenoid, midget, 120 VAC - 11.0 watts (2 each)
    - ASCP #8314C21
Heater tape, 1.75" W x 96.0" L, 120 VAC - 832 watts (1 each)
    - Cole Parmer # T-3107-80

TUBING (rigid and flexible)

2" schedule 5 pipe, S.S. (10 ft each)
5/8" O.D. x .049 wall, S.S. (10 ft each)
1/2" O.D. x .049 wall, S.S. (10+ ft each)
1/2" O.D. x .049 wall, copper (10 ft each)
3/8" O.D. x .035 wall, S.S. (5 ft each)
3/8" O.D. x .035 wall, copper (5 ft each)
1/4" O.D. x .035 wall, S.S. (20+ ft each)
1/4" O.D. x .035 wall, copper (10 ft each)

1/2" I.D. automobile heater hose (20 ft each)
1/2" I.D. x 3/32" wall, Tygon (2 ft each)
    - Sargent Welch #S-73650-G
3/8" I.D. x .125 wall, heavy wall, black neoprene (50 ft each)
    - Sargent Welch #S-73655-KF

1/4" I.D. SS braided Teflon hose (6 ft each)
    - McMaster Carr #5244K52
    - NOTE: requires purchase of special S.S. fittings (McMaster Carr #5244K82) which must be machined to desired geometry (4 each)

1/4" I.D. x 3/32" wall, heavy wall, black neoprene (50 ft each)
    - Sargent Welch #S-73655-KD

1/4" I.D. x 3/32" wall, Latex (1 roll)
    - Sargent Welch #S-73571-KD)

1/4" I.D. x 1/16" wall, Tygon (30 ft each)
    - Sargent Welch #S-73651-KC

MISCELLANEOUS

PM_{10} cyclone system (cyc I, cyc IV (if desired), and filter holder)
    - Andersen Samplers, Inc. #SE-280 Series

1/4 - 20 x 3" L bolt, washer, nut assembly; S.S. (1 each)

Assortment 1/4 - 20 x 1/2" L bolts, washers, nuts, S.S.

Assortment #10 x 3/4" L bolts, washers, nuts; S.S.

Assortment # 8 x 3/4" L bolts, washers, nuts; S.S.

Primer, zinc chromate (1 can each)

Enamel paint, peanut beige (1 can each)

Acrylic resin clear coat, gloss finish (1 can)
    - i.e. Datakoat Gloss

Lettering, rub-on style (lettering tool desired)
    - custom fabricated

Hand knob assembly, threaded 1/4 - 20, manometer level (1 each)
    - McMaster Carr 6085K12

Wave washers, 1/4" dia hole

Assorted 1/8" AL plate (for system support)

RTV silicone rubber, for weather proofing (1 tube each)

RTV silicone rubber, high temp. (1 tube)

Teflon tape (1 roll each)

Liquid thread sealant, (1 tube)

Pin stripping, red and blue, see umbilical assembly (1 each)

Expanding sleeve, nylon, 1.25" dia, for umbilical (25 ft each)
- Bentley Harris # 6762001-13
- Cole-Flex # XS-100

Expanding sleeve, nylon, 0.75" dia (10 ft each)
- available from above sources

Drying column, drierite or silica gel, 285 mm x 67 mm (1 each)
- Sargent Welch # S-28730

4 CFM pump, carbon vane, leak-free, w/muffler-filter (1 each)
- available through Andersen Samplers, Inc.

FABRICATED (Shop) ITEMS

EGR nozzle assemblies, 3 individual diameters
- SRI Dwg. No. 6211-21-01

Control box front panel, 1/8" AL plate
- SRI Dwg. No. 5785-1-C-01

Control box back panel, 1/8" AL plate
- SRI Dwg. No. 5785-1-C-04

Manometer leveling accessories, leveling guide & bolt base
- SRI Dwg. No. 5785-1-C-02

Gas meter supports, bottom & top supports
- SRI Dwg. No. 5785-1-C-03

Probe sheath, modified 2" Sch 5 SS pipe
- SRI Dwg. No. 5785-1-C-05

Probe caps, front & back, with front O-ring
- SRI Dwg. No. 5785-1-C-05

Sample orifice assemblies, 3 individual diameters
- SRI Dwg. No. 5785-1-B-06

Pitot clamp (1 each)
- SRI Dwg. No. 5785-1-C-08

Cyclone I modification, to allow pitot attachment

- SRI Dwg. No. 5785-1-C-08

Pitot flex-line fitting modification (4 each)

- SRI Dwg. No. 5785-1-c-08

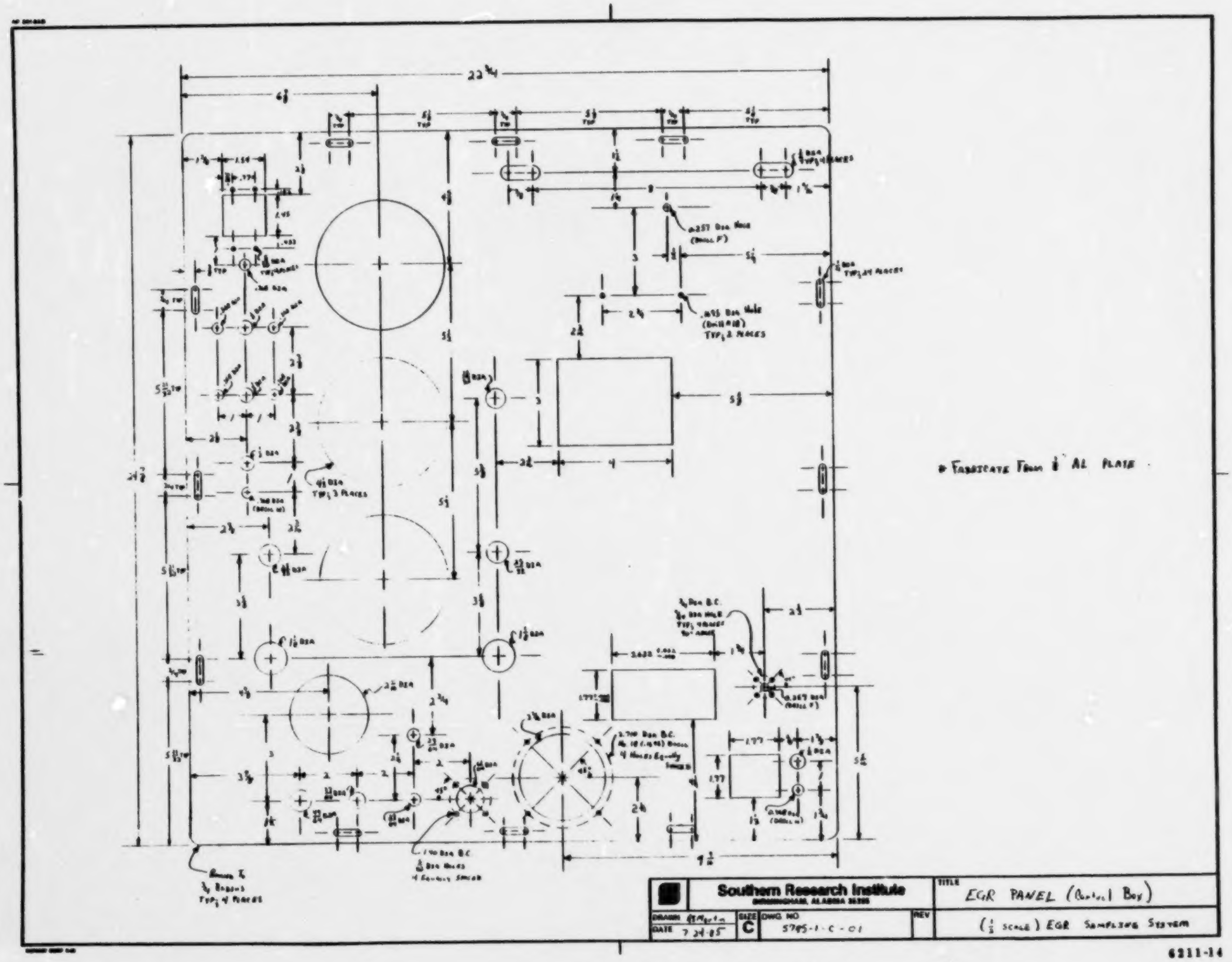
Coiled condenser, SS

- SRI Dwg. No. 4266-D-05

APPENDIX B

LIST OF EGR SYSTEM SHOP DRAWINGS

EGR panel (control box)
EGR sampling system, manometer leveling accessories
EGR sampling system, DGM supports
EGR sampling system, back panel: magnehelic zero valves
EGR sampling system, probe components
EGR sampling system, sample orifice assembly
EGR sampling system, EGR nozzle
EGR sampling system, pitot assembly
EGR sampling system, EGR circuit diagram
EGR sampling train, condenser


22 3/4
* Fabricate From 1/8" Al Plate
Southern Research Institute
Birmingham, Alabama 35205
TITLE
EGR PANEL (Control Box)
(1/2 scale) EGR Sampling System
DRAWN
DATE 7-24-85
SIZE C
DWG NO 5785-1-C-01
REV

6211-14

Figure B-1. EGR panel (control box).

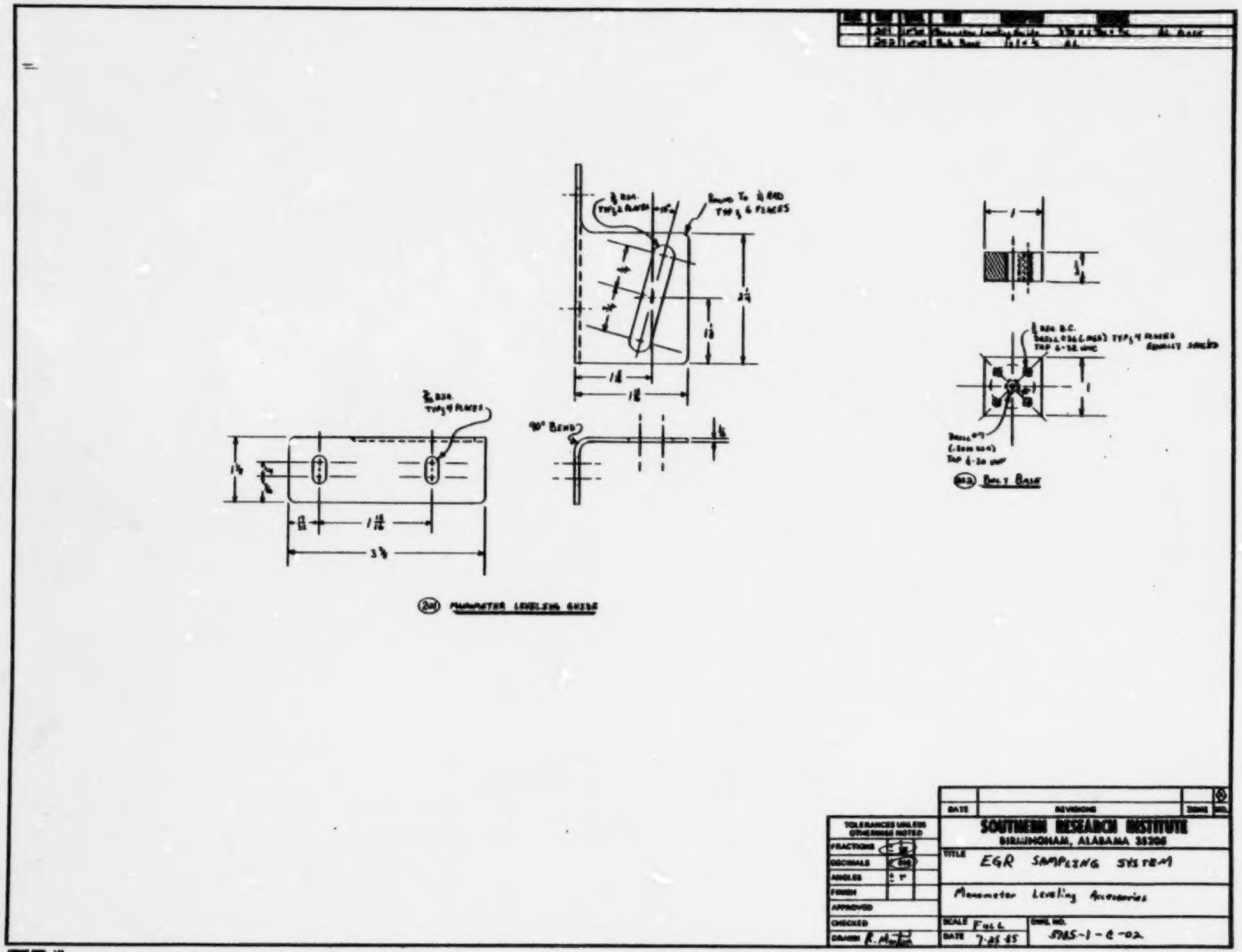

90° BEND
MANOMETER LEVELING GUIDE
BOLT BASE
3 1/8
1 11/16
SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA 35205
TOLERANCES UNLESS OTHERWISE NOTED
FRACTIONS
DECIMALS
ANGLES
FINISH
APPROVED
CHECKED
DRAWN
DATE
REVISIONS
TITLE
EGR SAMPLING SYSTEM
Manometer Leveling Accessories
SCALE Full
DATE 7-25-85
DWG NO.
5785-1-C-02
6211-6

Figure B-2. EGR sampling system, manometer leveling accessories.

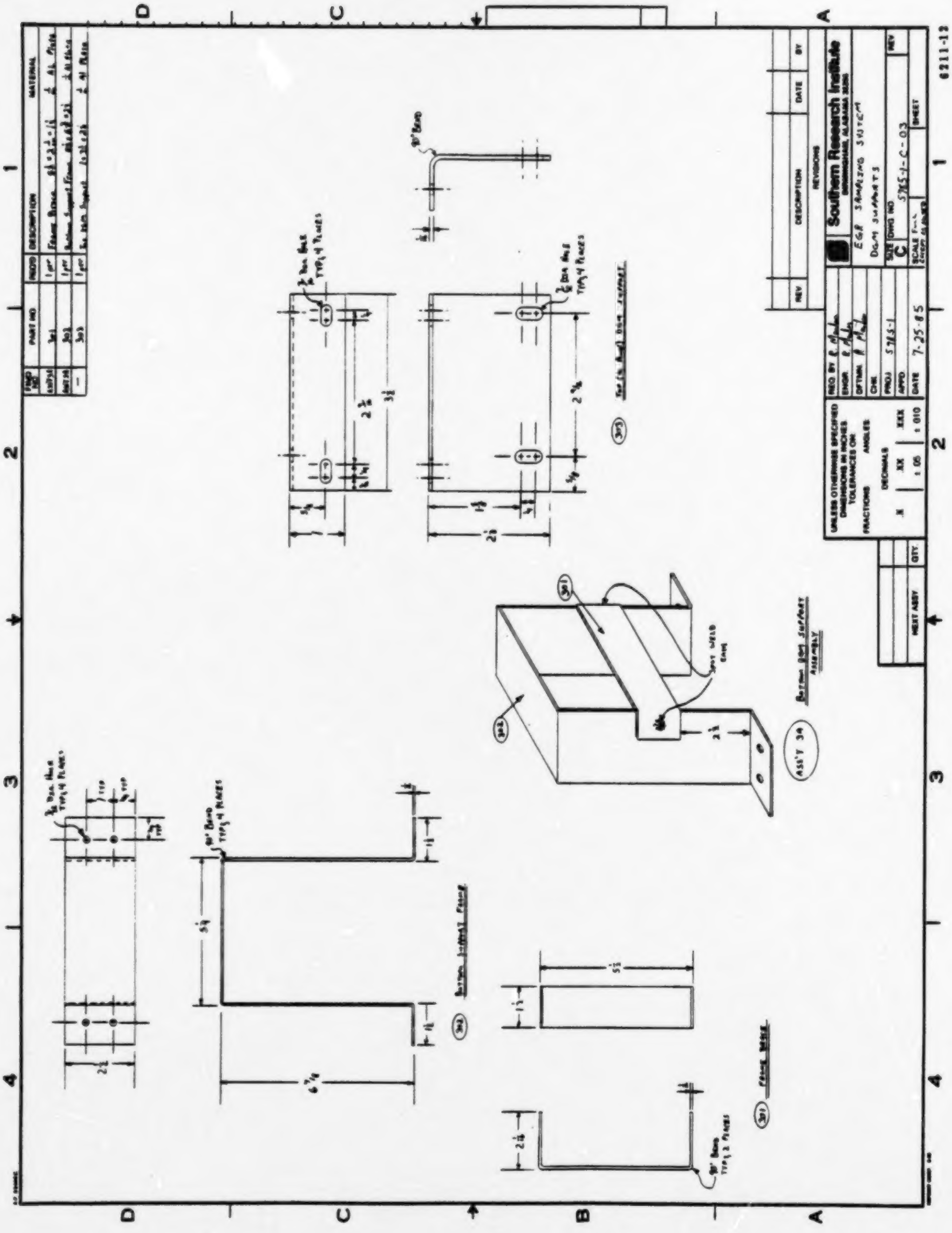
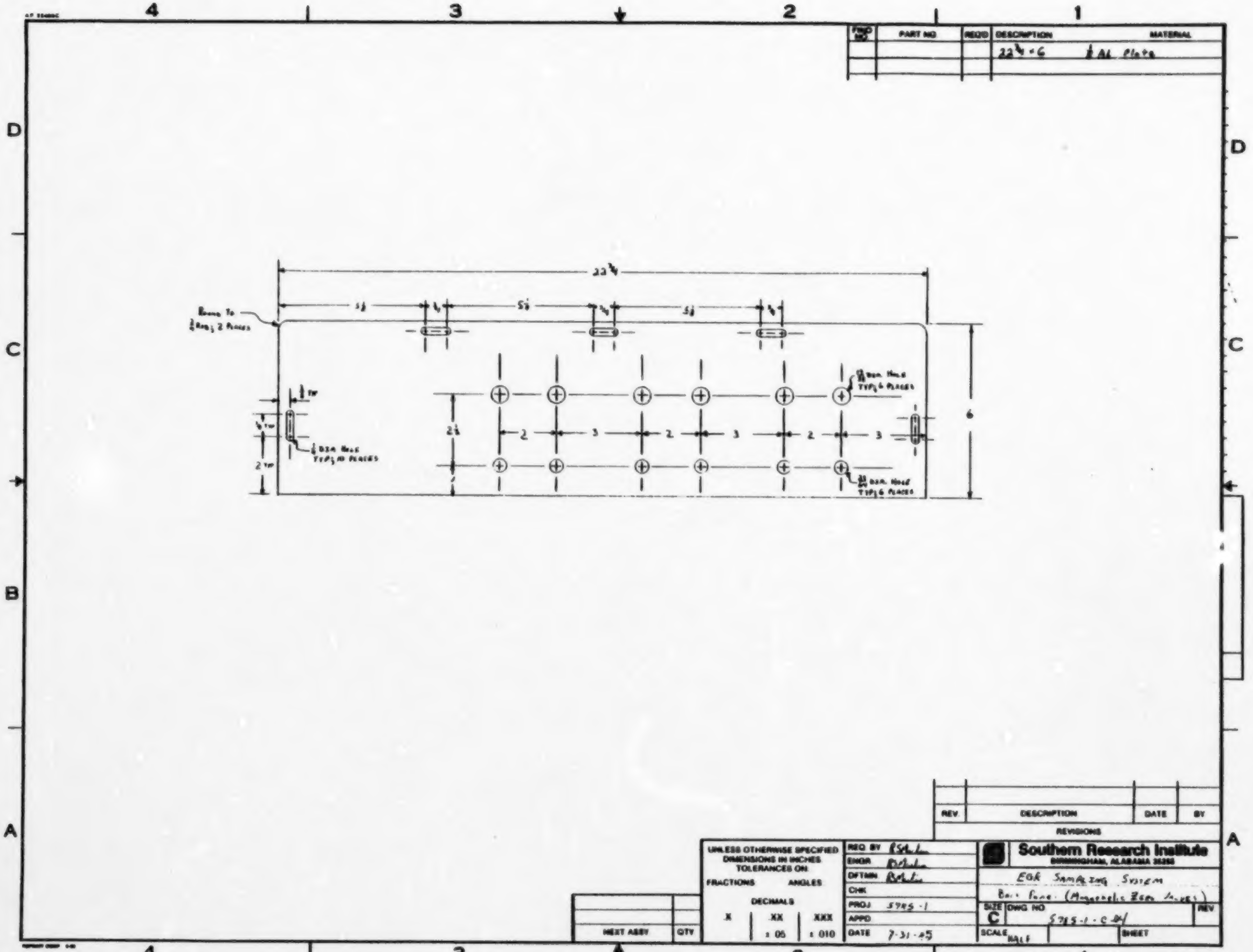

Southern Research Institute
BIRMINGHAM, ALABAMA 35255
EGR SAMPLING SYSTEM
DGM SUPPORTS
C
5785-11-C-03
SCALE FULL
7-25-85
PROJ 5785-1
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES ON
FRACTIONS
ANGLES
DECIMALS
.X
.XX ±.05
.XXX ±.010
REQ BY
ENGR
DFTSMN
CHK
APPD
DATE
REV
DESCRIPTION
DATE
BY
REVISIONS
SIZE
DWG NO
SHEET
NEXT ASSY
QTY
PART NO
DESCRIPTION
MATERIAL
301
302
303
ASS'Y 34
BOTTOM DGM SUPPORT ASSEMBLY
90° BEND
SPOT WELD
FRAME BASE
6211-12
A
B
C
D
1
2
3
4

Figure B-3. EGR sampling system, DGM supports.



4
3
2
1
D
C
B
A
FIND NO
PART NO
REQD
DESCRIPTION
MATERIAL
22¾ × 6
⅛ AL Plate
22¾
6
2
3
2 TYP
Round To ¼ Rad; 2 Places
¼ DIA Hole TYP; 10 Places
DIA Hole TYP; 6 Places
DIA Hole TYP; 6 Places
REV.
DESCRIPTION
DATE
BY
REVISIONS
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES ON
FRACTIONS
ANGLES
DECIMALS
X
XX
± .05
XXX
± .010
NEXT ASSY
QTY
REQ BY
ENGR
DFTMN
CHK
PROJ 5745-1
APPD
DATE 7-31-75
Southern Research Institute
BIRMINGHAM, ALABAMA 35255
EGR Sampling System
Back Panel (Magnehelic Zero Valves)
SIZE C
DWG NO 5745-1-C-84
REV
SCALE HALF
SHEET
6211-16

Figure B-4. EGR sampling system, back panel: magnehelic zero valves.

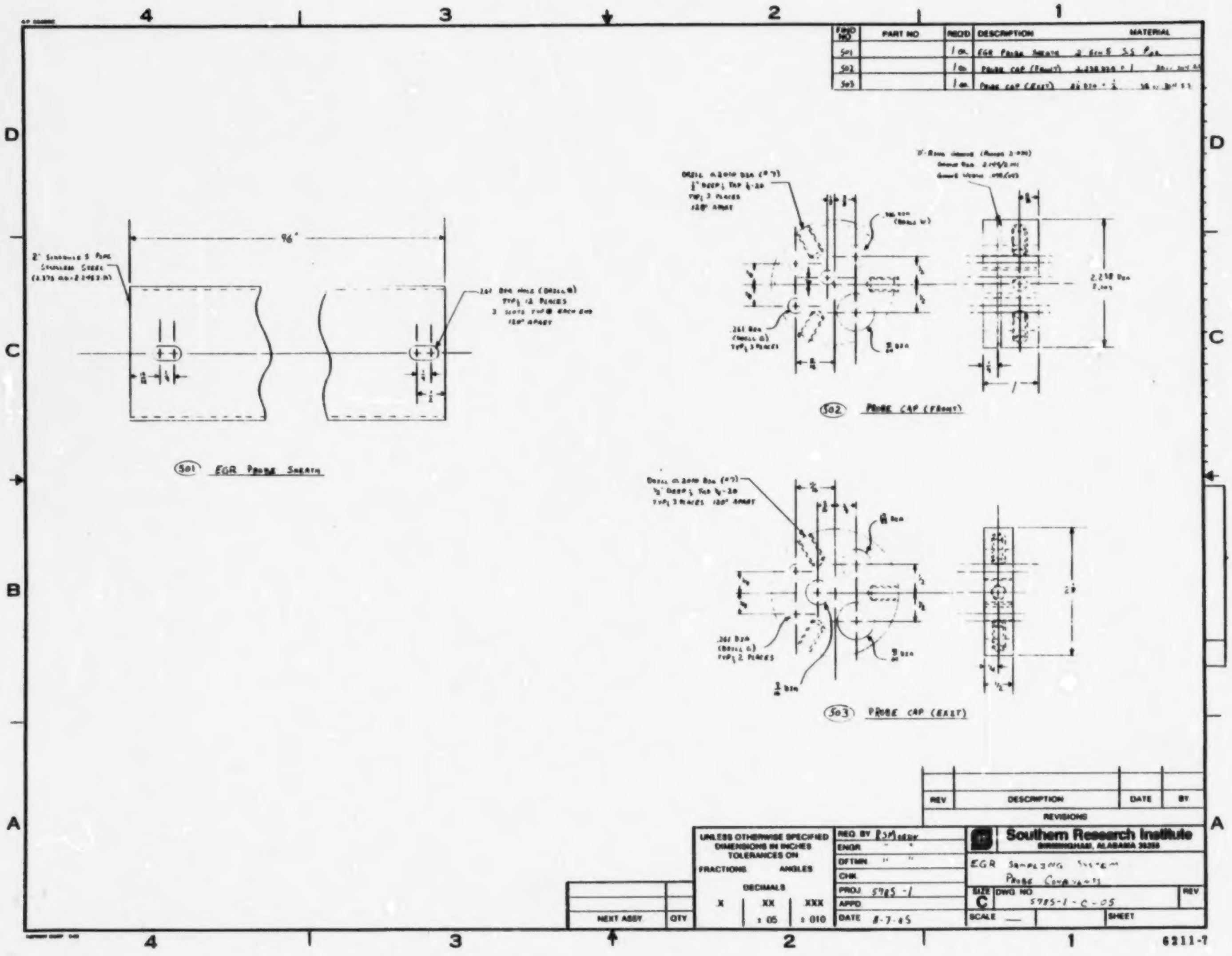
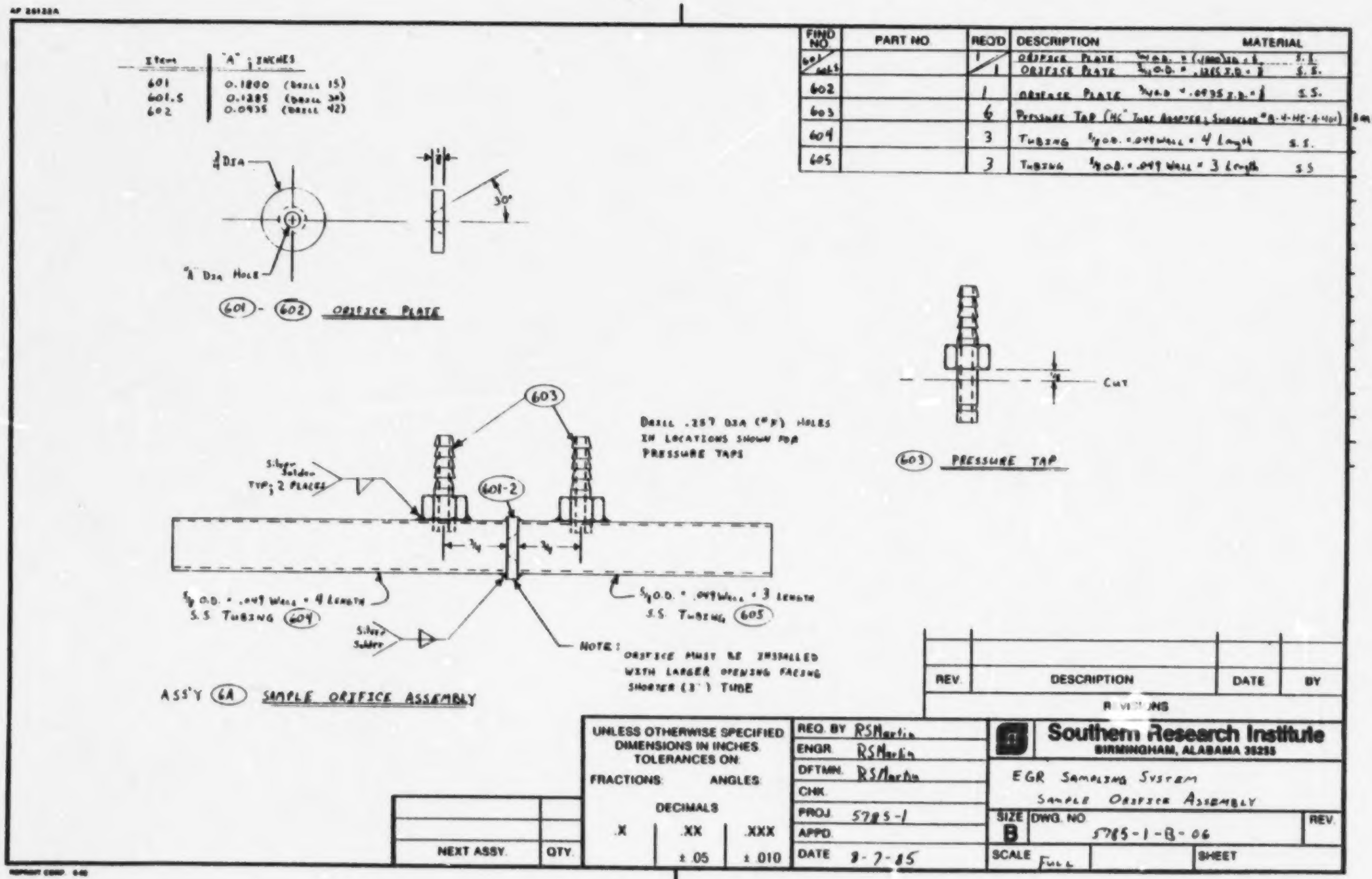

FIND NO
PART NO
REQD
DESCRIPTION
MATERIAL
501
1 ea.
EGR Probe Sheath
502
1 ea.
Probe Cap (Front)
503
1 ea.
Probe Cap (Exit)
96"
501 EGR Probe Sheath
502 Probe Cap (Front)
503 Probe Cap (Exit)
REV
DESCRIPTION
DATE
BY
REVISIONS
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES ON
FRACTIONS
ANGLES
DECIMALS
X
XX
XXX
± .05
± .010
NEXT ASSY
QTY
REQ BY RSMcCary
ENGR
DFTMN
CHK
PROJ 5785-1
APPD
DATE 8-7-85
Southern Research Institute
BIRMINGHAM, ALABAMA 35255
EGR Sampling System
Probe Components
SIZE C
DWG NO 5785-1-C-05
REV
SCALE —
SHEET
A
B
C
D
1
2
3
4
6211-7

Figure B-5. EGR sampling system, probe components.


AF 26133A
Item | "A" ; INCHES
601 | 0.1800 (DRILL 15)
601.5 | 0.1285 (DRILL 30)
602 | 0.0935 (DRILL 42)
3/4 DIA
"A" DIA HOLE
30°
601 - 602 ORIFICE PLATE
603
601-2
Silver Solder TYP; 2 PLACES
Silver Solder
DRILL .257 DIA ("F") HOLES IN LOCATIONS SHOWN FOR PRESSURE TAPS
3/4
5/16 O.D. × .049 WALL × 4 LENGTH S.S. TUBING 604
5/16 O.D. × .049 WALL × 3 LENGTH S.S. TUBING 605
NOTE: ORIFICE MUST BE INSTALLED WITH LARGER OPENING FACING SHORTER (3") TUBE
ASS'Y 6A SAMPLE ORIFICE ASSEMBLY
603 PRESSURE TAP
CUT
FIND NO | PART NO | REQ'D | DESCRIPTION | MATERIAL
601 / 601.5 | | 1 / 1 | ORIFICE PLATE 5/16 O.D. × (.1800) I.D. × 1/8 / ORIFICE PLATE 5/16 O.D. × .1285 I.D. × 1/8 | S.S. / S.S.
602 | | 1 | ORIFICE PLATE 5/16 O.D. × .0935 I.D. × 1/8 | S.S.
603 | | 6 | PRESSURE TAP (1/16" TUBE ADAPTER; SWAGELOK #B-4-HC-A-401) | BRASS
604 | | 3 | TUBING 5/16 O.D. × .049 WALL × 4 Length | S.S.
605 | | 3 | TUBING 5/16 O.D. × .049 WALL × 3 Length | S.S.
REV. | DESCRIPTION | DATE | BY
REVISIONS
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES ON:
FRACTIONS: ANGLES:
DECIMALS
.X | .XX ± .05 | .XXX ± .010
NEXT ASSY. | QTY.
REQ. BY RSMartin
ENGR RSMartin
DFTMN. RSMartin
CHK.
PROJ. 5785-1
APPD.
DATE 8-7-85
Southern Research Institute
BIRMINGHAM, ALABAMA 35255
EGR Sampling System
Sample Orifice Assembly
SIZE B
DWG. NO. 5785-1-B-06
REV.
SCALE Full
SHEET

6211-13

Figure B-6. EGR sampling system, sample orifice assembly.

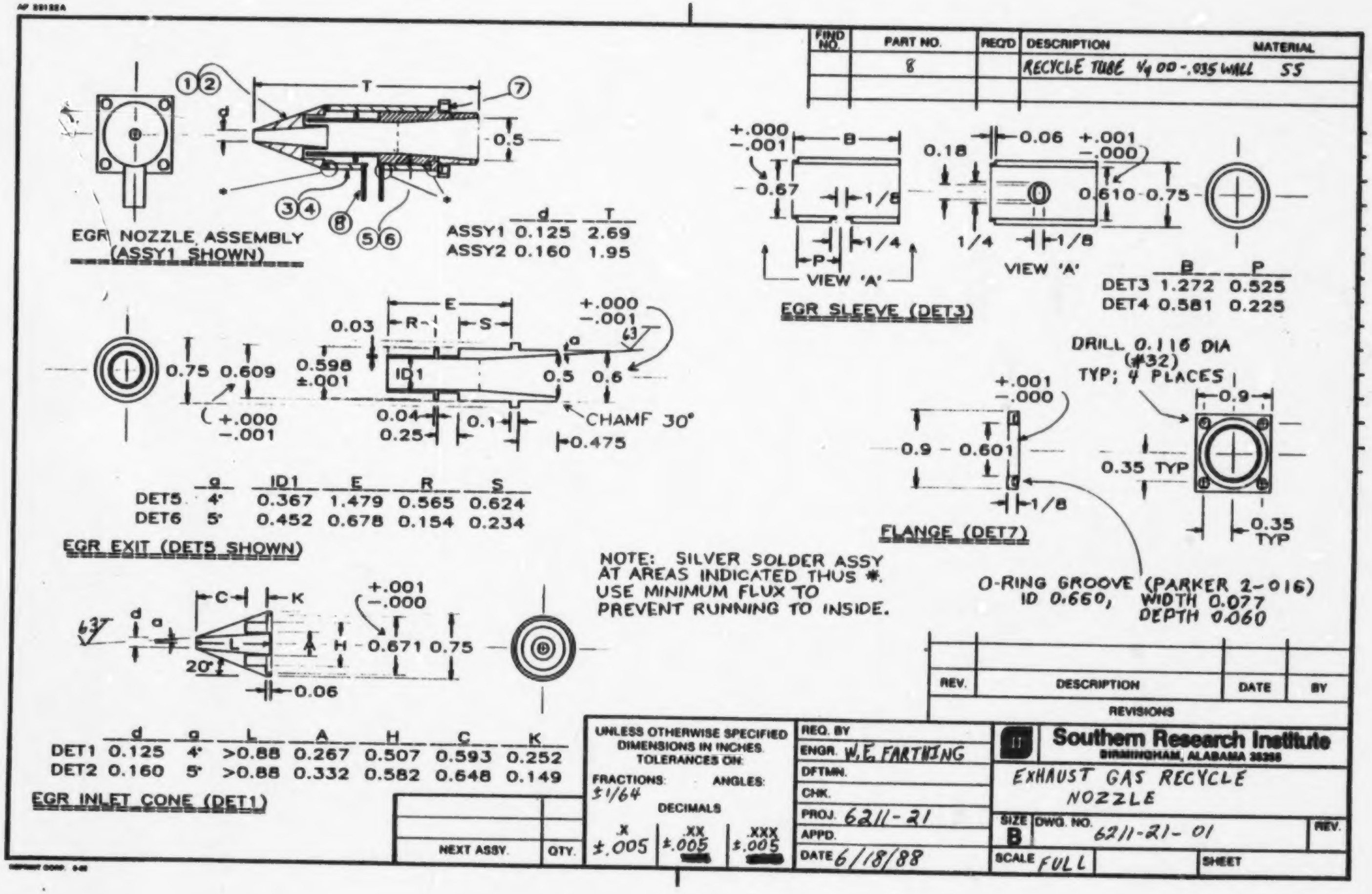

FIND NO. | PART NO. | REQ'D | DESCRIPTION | MATERIAL
8 | RECYCLE TUBE ¼ OD -.035 WALL | SS
EGR NOZZLE ASSEMBLY (ASSY1 SHOWN)
① ② ③ ④ ⑤ ⑥ ⑦ ⑧
T
d
0.5
d T
ASSY1 0.125 2.69
ASSY2 0.160 1.95
EGR SLEEVE (DET3)
+.000 −.001
B
0.67
1/8
1/4
P
VIEW 'A'
0.18
0.06 +.001 −.000
0.610 0.75
1/4 1/8
VIEW 'A'
B P
DET3 1.272 0.525
DET4 0.581 0.225
EGR EXIT (DET5 SHOWN)
0.75 0.609
+.000 −.001
0.598 ±.001
0.03
E
R
S
ID1
0.5 0.6
+.000 −.001
63
a
0.04
0.25
0.1
CHAMF 30°
0.475
a ID1 E R S
DET5 4° 0.367 1.479 0.565 0.624
DET6 5° 0.452 0.678 0.154 0.234
FLANGE (DET7)
+.001 −.000
0.9 − 0.601
1/8
DRILL 0.116 DIA (#32) TYP; 4 PLACES
0.9
0.35 TYP
0.35 TYP
O-RING GROOVE (PARKER 2-016) ID 0.660, WIDTH 0.077 DEPTH 0.060
NOTE: SILVER SOLDER ASSY AT AREAS INDICATED THUS *. USE MINIMUM FLUX TO PREVENT RUNNING TO INSIDE.
EGR INLET CONE (DET1)
63
d a
C K
+.001 −.000
H 0.671 0.75
A
L
20°
0.06
d a L A H C K
DET1 0.125 4° >0.88 0.267 0.507 0.593 0.252
DET2 0.160 5° >0.88 0.332 0.582 0.648 0.149
REV. DESCRIPTION DATE BY
REVISIONS
NEXT ASSY. QTY.
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES ON:
FRACTIONS: ±1/64 ANGLES:
DECIMALS
.X ±.005 .XX ±.005 .XXX ±.005
REQ. BY
ENGR. W.E. FARTHING
DFTMN.
CHK.
PROJ. 6211-21
APPD.
DATE 6/18/88
Southern Research Institute
BIRMINGHAM, ALABAMA 35255
EXHAUST GAS RECYCLE NOZZLE
SIZE B DWG. NO. 6211-21-01 REV.
SCALE FULL SHEET

Figure B-7. EGR sampling system, EGR nozzle.

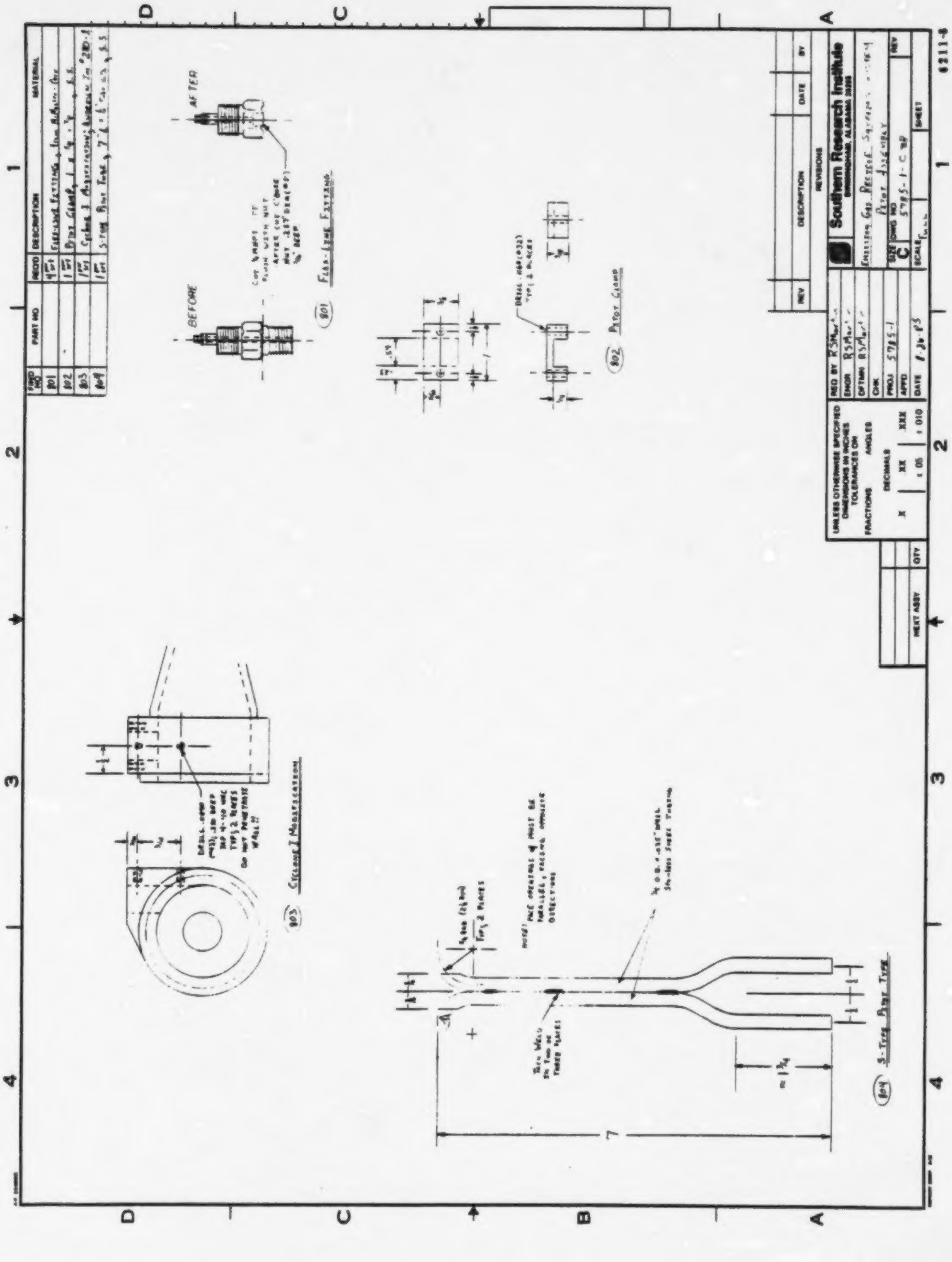
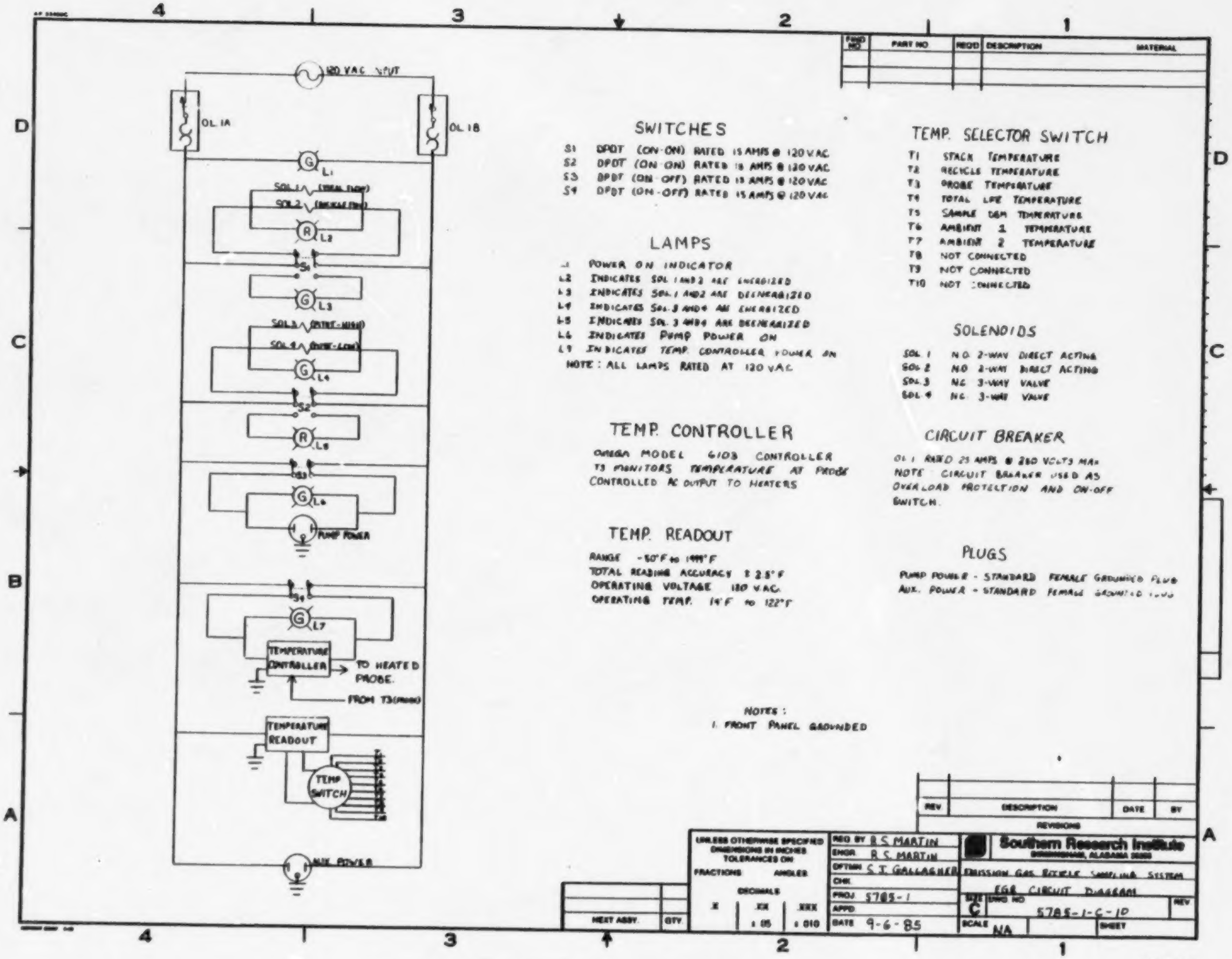

Southern Research Institute
Birmingham, Alabama
Pitot Assembly
BEFORE
AFTER
801 Ferrule Fitting
802 Pitot Gland
803 Cyclone I Modification
804 S-Type Pitot Tube
7
≈ 1¾
REVISIONS
FIND NO
PART NO
REQ'D
DESCRIPTION
MATERIAL
NEXT ASSY
QTY
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES
TOLERANCES ON
FRACTIONS
ANGLES
DECIMALS
X
XX ±.05
XXX ±.010
REQ BY
ENGR
DFTMN
CHK
PROJ
APPD
DATE
SIZE C
DWG NO
SCALE
SHEET
REV
A
B
C
D
1
2
3
4

Figure B-8. EGR sampling system, pitot assembly.



120 VAC INPUT
OL 1A
OL 1B
L1
SOL 1
SOL 2
L2
S1
L3
SOL 3
SOL 4
L4
S2
L5
S3
L6
PUMP POWER
S4
L7
TEMPERATURE CONTROLLER
TO HEATED PROBE.
FROM T3
TEMPERATURE READOUT
TEMP SWITCH
AUX POWER
SWITCHES
S1 DPDT (ON-ON) RATED 15 AMPS @ 120 VAC
S2 DPDT (ON-ON) RATED 15 AMPS @ 120 VAC
S3 DPDT (ON-OFF) RATED 15 AMPS @ 120 VAC
S4 DPDT (ON-OFF) RATED 15 AMPS @ 120 VAC
LAMPS
L1 POWER ON INDICATOR
L2 INDICATES SOL 1 AND 2 ARE ENERGIZED
L3 INDICATES SOL 1 AND 2 ARE DEENERGIZED
L4 INDICATES SOL 3 AND 4 ARE ENERGIZED
L5 INDICATES SOL 3 AND 4 ARE DEENERGIZED
L6 INDICATES PUMP POWER ON
L7 INDICATES TEMP. CONTROLLER POWER ON
NOTE: ALL LAMPS RATED AT 120 VAC
TEMP. CONTROLLER
OMEGA MODEL 6103 CONTROLLER
T3 MONITORS TEMPERATURE AT PROBE
CONTROLLED AC OUTPUT TO HEATERS
TEMP. READOUT
RANGE -50°F to 1999°F
TOTAL READING ACCURACY ± 2.5°F
OPERATING VOLTAGE 120 VAC.
OPERATING TEMP. 14°F to 122°F
TEMP. SELECTOR SWITCH
T1 STACK TEMPERATURE
T2 RECYCLE TEMPERATURE
T3 PROBE TEMPERATURE
T4 TOTAL LINE TEMPERATURE
T5 SAMPLE DGM TEMPERATURE
T6 AMBIENT 1 TEMPERATURE
T7 AMBIENT 2 TEMPERATURE
T8 NOT CONNECTED
T9 NOT CONNECTED
T10 NOT CONNECTED
SOLENOIDS
SOL 1 N.O. 2-WAY DIRECT ACTING
SOL 2 N.O. 2-WAY DIRECT ACTING
SOL 3 N.C. 3-WAY VALVE
SOL 4 N.C. 3-WAY VALVE
CIRCUIT BREAKER
OL 1 RATED 25 AMPS @ 250 VOLTS MAX
NOTE CIRCUIT BREAKER USED AS OVERLOAD PROTECTION AND ON-OFF SWITCH.
PLUGS
PUMP POWER - STANDARD FEMALE GROUNDED PLUG
AUX. POWER - STANDARD FEMALE GROUNDED PLUG
NOTES:
1. FRONT PANEL GROUNDED
FIND NO
PART NO
REQD
DESCRIPTION
MATERIAL
REV
DESCRIPTION
DATE
BY
REVISIONS
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES ON
FRACTIONS
ANGLES
DECIMALS
.X
.XX ±.05
.XXX ±.010
NEXT ASSY
QTY
REQ BY R.S. MARTIN
ENGR R.S. MARTIN
DFTMN S.T. GALLAGHER
CHK
PROJ 5785-1
APPD
DATE 9-6-85
Southern Research Institute
BIRMINGHAM, ALABAMA
EMISSION GAS RECYCLE SAMPLING SYSTEM
EGR CIRCUIT DIAGRAM
SIZE C
DWG NO 5785-1-C-10
REV
SCALE NA
SHEET
A
B
C
D
1
2
3
4

6311-18

Figure B-9. EGR sampling system, EGR circuit diagram.

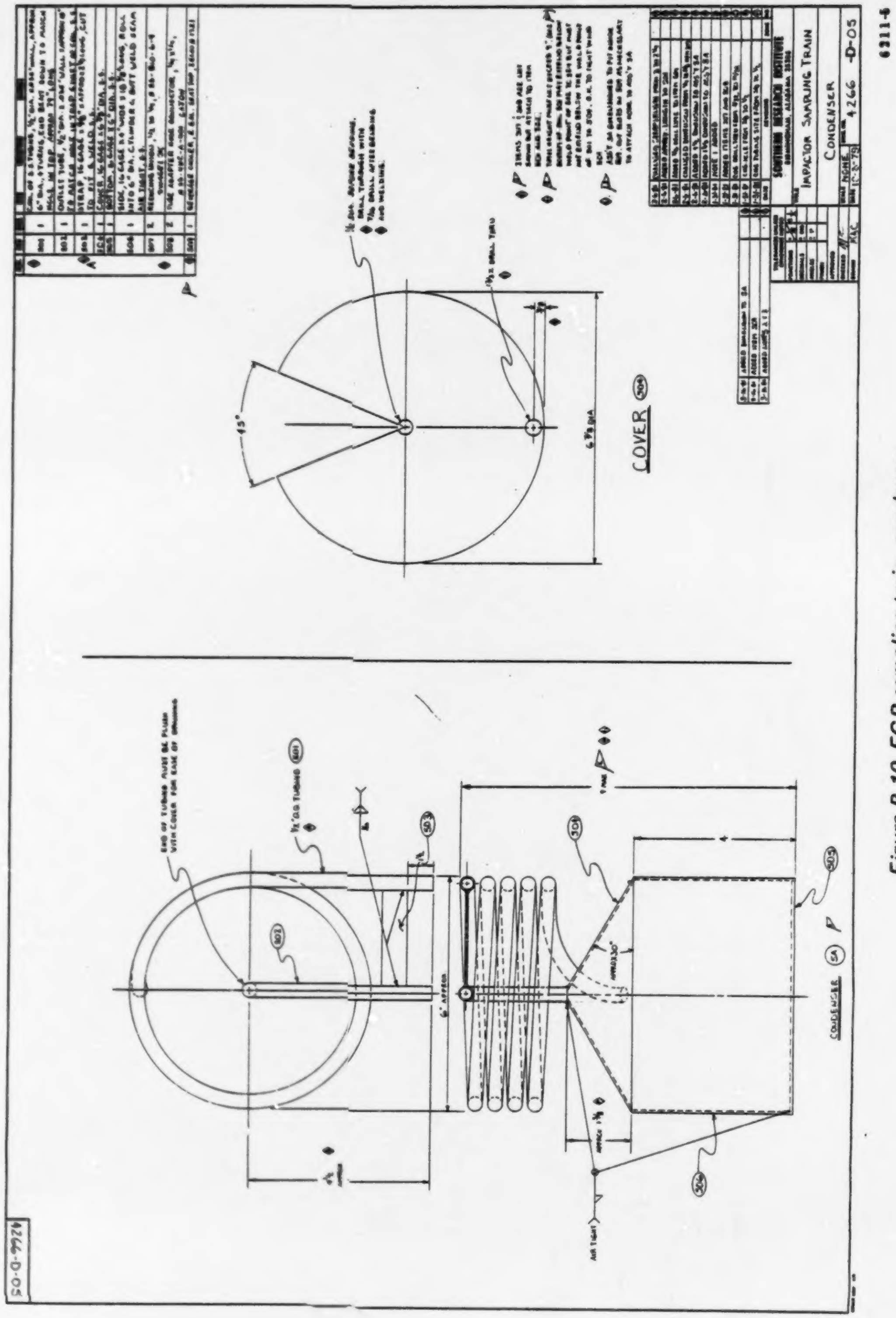

4266-D-05
CONDENSER
5A
6" APPROX
1/2" O.D. TUBING
501
502
503
504
505
506
AIR TIGHT
COVER
504
45°
6 3/8 DIA
SOUTHERN RESEARCH INSTITUTE
IMPACTOR SAMPLING TRAIN
CONDENSER
4266 -D-05
6311-6

Figure B-10. EGR sampling train, condenser.

APPENDIX C

LIST OF BLANK FORMS

Dry Gas Meter/Orifice Calibration Sheet
LFE Calibration Sheet
Pitot Calibration Sheet
Nozzle Calibration Form
Temperature Sensor Calibration Form
Magnehelic Gauge Calibration Check
System Vacuum Gauge Calibration Check
Field Barometer Calibration Form
Triple Beam Balance Calibration Form
Fyrite Analyzer Calibration Form
Method 1 Data Sheet
Method 2 Data Sheet
Method 3 Data Sheet
Method 4 Data Sheet
EGR Field Data Sheet
Lab Load/Unload Sheet
Field Sample Weight Sheet
Reagent Blank Evaluation Form

DRY GAS METER/ORIFICE (STANDARD: TEST METER) CALIBRATION SHEET

Sheet I.D.____

Dry Gas Meter I.D.________________ Standard Test Meter I.D.____________________

Barometric Pressure, P_B _______ in. Hg; Orifice I.D. ____________________

Calibrated by: ___________ Date: ____________ Leak Check: _______________

Run #	1	2	3	4	Avg
Orifice Setting, ΔH					
Final Reading (STM)					
Initial Reading (STM)					
Volume V_T, ft^3					
Temp T_T, °F					
ΔP_T, in. H_2O					
Final Reading (DGM)					
Initial Reading (DGM)					
Volume V_{DGM}, ft^3					
Temp T_{DGM}, °F					
Elapsed Time θ, min.					
DGM Flow Rate Q, acfm					
$\alpha = \left[\frac{\Delta H(T_{DGM}+460)}{(P_B+\frac{\Delta H}{13.6})MW_D}\right]$					
$\Delta H@_i$					
Correction Factor, γ_i					
% Error = $(\frac{\bar{\gamma}}{\gamma_i} - 1)$ 100%					

Previous Calibration:

Date:______________

Old γ ______________

Orifice ΔH from:

____ Manometer

____ Magnehelic

Zero ______________

Equipment Set Up:

___Positive Pressure (M5 w/leakless pump)

___Other

$$\Delta H@ = \frac{(0.0317)\Delta H}{P_B(T_{DGM}+460)}\left[\frac{(T_T+460)}{V_T}\theta\right]^2; \quad \gamma = \frac{V_T(P_B+\frac{\Delta P_T}{13.6})(T_{DGM}+460)}{V_{DGM}(P_B+\frac{\Delta H}{13.6})(T_T+460)}$$

Deviation = $\left(\frac{\bar{\gamma}_{new} - \bar{\gamma}_{previous}}{\bar{\gamma}_{previous}}\right)$ 100% = ___________ Note: Must be within ±5%.

Note: γ_i criteria (±2%); (MW_D is Dry molecular weight (28.97 for Standard air). If a Laminar Flow Element is substituted for the Standard Test Meter the STM columns may be used to record ΔP_{LFE} (in. H_2O) and ΔP_{SYS} (gauge pressure at orifice inlet, in. H_2O) if different from ΔH. For a Positive Pressure equipment arrangement $\Delta P_{SYS} = \Delta H$.

LFE CALIBRATION SHEET USING WET TEST METER

LFE I.D. ____________

DATE: ____________

OPERATOR: ____________

This calibration uses the fit:

$$Q_{LFE} = X \Delta P \left(\frac{\mu_{STD}}{\mu_{LFE}}\right) + Y$$

where: Q = LFE flowrate

ΔP = pressure drop

M_{LFE} = Gas viscosity at LFE

X,Y = Calibration constants

BAROMETRIC PRESSURE (In Hg) = ______

TEMPERATURES (°F):

Ambient = ______

LFE = ______

VISCOSITY (STD) = 180.1 micropoise

VISCOSITY (LFE) = $163.526 + 0.2552 (T_{LFE}) + 3.2355 \times 10^{-5} (T_{LFE})^2$

= ______ micropoise (Note: For T_{LFE} in °F)

RUN	WTM VOLUME (Ft^3)	TIME (min)	DP LFE (In H_2O)	DP System (In H_2O)	Q WTM (ACFM)	Q LFE (ACFM)
1						
2						
3						
4						
5						
6						
7						
8						

NOTE: D_p system is the pressure differential between the LFE inlet and ambient.

$$Q_{LFE} = \left[\frac{V_{(WTM)}}{Time}\right] \left[\frac{P_{AMB}}{P_{AMB} + \left(\frac{DP\ syst}{13.6}\right)}\right] \left[\frac{(T_{LFE} + 460)}{(T_{WTM} + 460)}\right]$$

Calibration Results: X = ______ Y = ______

Sheet I.D.____

Pitot Calibration Sheet

Pitot I.D. ____________________

Date ____________________

Operator ____________________

$C_{p(STD)}$ ____________________

Leak Check? ________________________

Manometers/Magnehelics Zeroed?________

Sketch or describe configuration:

ΔP_{STD} (in. H_2O)	ΔP_{TEST} (in. H_2O)	$C_{p(TEST)}$	Deviation

Average		

$$C_{p(TEST)} = C_{p(STD)} \sqrt{\frac{\Delta P_{STD}}{\Delta P_{TEST}}}$$

$$DEV_{(i)} = C_{p(i)} - \bar{C}p \text{ (must be within } \pm 0.01)$$

where $C_{p(TEST)}$ = pitot tube coefficient of Type S pitot tube, dimensionless,

$C_{p(STD)}$ = pitot tube coefficient of standard (if unknown use 0.99) type

ΔP_{STD} = standard pitot tube velocity head, inches H_2O, and

ΔP_{TEST} = Type S pitot tube velocity head, inches H_2O.

Nozzle Calibration Form
(See Instructions Below)

Sheet I.D._____

Date/Time	Calibrated By	Nozzle ID Number	Nozzle Diameter (inches)			ΔD	D_{avg}
			D_1	D_2	D_3		

where:

$D_{1,2,3}$ = three different nozzle diameters at 60 degrees to each other. Each measured to the nearest 0.001 inch

ΔD = maximum difference between any two diameters, $\Delta D < 0.004$ inch

$D_{avg} = (D_1 + D_2 + D_3) \div 3$

Instructions

1. Inspect the nozzle for nicks, dents, and corrosion. If these are found they should be corrected before calibration.
2. Place a reference mark on the nozzle. Place the nozzle at the center of Figure 1, aligned with Point 1. Measure and record D_1.
3. Rotate the nozzle so that the reference mark is aligned with Point 2. Measure and record D_2.
4. Rotate the nozzle so that the reference mark is aligned with Point 3. Measure and record D_3.
5. Calculate ΔD and D_{avg}.

Sheet I.D.____

TEMPERATURE SENSOR CALIBRATION DATA FORM

Date ____________________

Ambient Temperature ________ °F

Calibrated by ____________

Thermocouple I.D. No.____________

Potentiometer I.D. No.____________

Barometric Pressure ________ in. Hg

Ref: Mercury-in-glass ____________
Other ____________

Reference Point No.	Source (specify)	Reference Thermometer Temperature, °F	Thermocouple Potentiometer Temperature, °F	Temperature Difference,[a] %

$$^{a}\left[\frac{(\text{ref. temp, °F} + 460) - (\text{test thermom temp, °F} + 460)}{(\text{ref temp, °F} + 460)}\right] 100\%$$

Note: Temperature difference must be within ±1.5%.

Sheet I.D._____

MAGNEHELIC GAUGE CALIBRATION CHECK

Date ____________________ Gauge I.D. ______________________

Ambient Temp _____________ °F Calibrated by:___________________

Barometric Press. ________in. Hg Leak Check:

Pos. @_____ "H_2O Acceptable _____

Neg. @_____ "H_2O Acceptable _____

	Manometer ΔP (in. H_2O)	MAGNEHELIC ΔP (in. H_2O)	Deviation $(\frac{Man-Mag.}{Man.})100\%$
Positive Side			
Negative Side			

Calibrate and leak check the differential pressure gauge using the following procedure:

1. Connect the differential pressure gauge to a gauge-oil manometer, as shown.
2. Vent the vacuum side to the atmosphere, and place pressure on each system to approximately maximum gauge reading. Close system and observe gauge reading for one minute. If no change in reading occurs, leak check is acceptable.
3. Compare Δp readings of the differential pressure gauge with those of the gauge-oil manometer at a minimum of three points representing approximately the range of Δp values to be encountered. Follow the same procedures on the vacuum side by venting the pressure side to the atmosphere and by putting a vacuum on the system.
4. During a pretest calibration check if, at each point, the value of Δp as read by the differential pressure gauge and the gauge-oil manometer agree within 5%, the differential pressure gauge should be considered properly calibrated.
5. The posttest calibration should be performed at the average Δp. If the agreement is within ±5% the calibration is acceptable; if not, refer to EPA Reference Method 2 to determine acceptability.

Sheet I.D. _____

SYSTEM VACUUM GAUGE CALIBRATION CHECK

Date ______________________ Gauge I.D. ______________________

Ambient Temp ______________ °F Calibrated by ______________________

Barometric Press. _________ in. Hg Leak Rate (cfm) ______________________

Mercury Manometer (in. Hg)	Vacuum Gauge (in. Hg)	Correction Factor

1. Assemble system as shown. Note: Mercury manometer should have at least 24" vacuum capacity.
2. System leack check: With pinch clamp closed, adjust system vacuum to 20 "Hg (manometer), observe gas meter flowrate (must be <0.02 cfm).
3. If leak rate is acceptable, adjust system vacuum to 15 and 19" Hg. Record each comparison. The vacuum gauge reading should be within ±10% of the reference.

Correction Factor, $CF_v = \frac{\text{Manometer}}{\text{Vacuum Gauge}}$

Sheet I.D.______

Field Barometer Calibration Form

Field Barometer I.D. ___________________

Calibration Source ____________________

The field barometer should be adjusted initially and before each test series to agree within ±2.5 mm (0.1 in) Hg of a mercury-in-glass barometer or with the station pressure value reported by a nearby National Weather Service station and corrected for elevation. The correction for elevation difference between the station and the sampling point should be applied at a rate of -2.4 mm Hg/30 m (-0.1 in Hg/100 ft).

Was the pretest field barometer calibrated? ______ yes _____ no

Operator: ____________________

Date: ________________________

Reference Pressure = ________________

Difference = _____________

Measured Pressure = ________________

Triple Beam Balance
Calibration Form

(See Instructions Below)

Date: ____________________ Zero: ____________________

Operator: ____________________________

	Reference Wt. (g)	Measured Wt. (g)	Difference (g)
1			
2			
3			
4			
5			

Instructions:

The triple beam balance should be calibrated by using Class-S standard weights and should be within ±0.5 g of the standard weight. Adjust or return the balance to the manufacturer if limits are not met.

Fyrite Analyzer Calibration Form

Date: ______________________ Operator: ____________________________

		Oxygen			Carbon Dioxide		
	Zero (✓)	Source	Reading	% Error	Source	Reading	% Error
1							
2							
3							
		Average			Average		

NOTE: If Oxygen Source is ambient air, the measured average must be 20.8 ± 0.7%. If Source is a known mixture of gases, the average should be ± 0.5% of known concentration for both oxygen and carbon dioxide.

METHOD 1. DATA SHEET

Instructions: Draw port configuration on appropriate duct geometry.

Duct Diameter ____ in.

No. Diameters to nearest upstream disturbance ____

No. Diameters to nearest downstream disturbance ____

No. Required traverse points ____

Port flange depth ____ in.

Duct dimensions ____ in.

Equivalent diameter, $De = \frac{2\ LW}{L+W}$ ____ in.

No. Diameters to nearest upstream disturbance ____

No. Diameters to nearest downstream disturbance ____

No. Required traverse points ____

Port flange depth ____

Point No	Position of traverse points (Distance from inner wall in inches)
1	
2	
3	
4	
5	

Method 2 Data Sheet

Plant: ______________________ Date: ______________

Location: ______________________ Time: ______________

$\%O_2$= ________ $\%N_2$= ________ $\%CO_2$= ________ %CO= ________ $\%H_2O$= ________

P_{amb} (HG)= ________ $\pm\Delta P_{stack}(H_2O)$= ________ T_{amb}(°F)= ________

Pitot Constant= ________

Point No.	Port 1		Port 2		Port 3		Port 4		Port 5		Port 6		Port 7		Port 8		Port 9	
	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T	ΔP_v	T
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
Avg.*																		

* Averages are $\sqrt{\Delta p}$, not Δp.

AVERAGE DUCT VELOCITY = ________

AVERAGE DUCT TEMPERATURE = ________

METHOD 3 DATA SHEET

Test Name: ______________________________

Sample Location: ______________________________

FYRITE GAS ANALYSIS

Date	Time	$\%O_2$	$\%CO_2$	Operator

METHOD 4 - WATER ANALYSIS

Date	Time	Run I.D.	Water Collected, mℓ	DGM Volume, Vm, Ft^3		DGM Temp, Tm, °R	Barometric Press, Pm	Bw_0 % H_2O	Operator
				Initial	Final				

V_{wc} = (0.0472 ft^3/ml) (Water Collected)

V_{me} = (17.65 °R/in. Hg) $\left(\frac{V_m P_m}{T_m} \right)$ $\qquad B_{wo} = \frac{V_{wc}}{V_{wc} + V_{me}} + 0.025$

Run Code	Date	Stack Temperature (°F)	Gas Composition %CO_2 %O_2 %CO
Sampler ID	Start Time	Differential Stack Pressure (in.H_2O)	Moisture Content
Filter ID	End Time	Ambient Temperature (°F)	
Sampler Orientation	Sampling Duration (min)	Ambient Pressure (in.Hg)	
Sampling Location	DGM (initial)	Gas Velocity	Pitot Leak Check (Pos) (Neg)
Nozzle Diameter-ID (in)	DGM (final)	System Leak Check	Notes
Operator(s)	Sample Volume (ft^3)		
Dual Manometer Leveled and Zeroed?			
Magnehelics Zeroed?			

Run Time	Port No / Trav.Pt.	ΔP Pitot	ΔH Sample	DGM Volume	ΔP Total	P Inlet	ΔP Recycle	T_1 Stack	T_2 Recycle	T_3 Probe	T_4 LFE	T_5 DGM

LAB LOAD/UNLOAD SHEET FOR MT FILTER, PM10, OR 5 SERIES CYCLONE

RUN CODE

ORIFICE ID
(USED FOR CALCULATING RUN PARAMETERS)

SAMPLING ASSIGNMENT
INLET, OUTLET, OTHER:

SUBSTRATE SET
IDENTIFICATION

SAMPLER ID NUMBERS
HOLDER NO. ______________________________
NOZZLE ID NO. ______________________________
NOZZLE DIAMETER ______________________________ (INCHES)

PERSON LOADING IMPACTOR AND DATE LOADED

- LOAD SAMPLER
- MARK HOLDER WITH RUN CODE
- LEAK TEST
- WRAP WITH FOIL AND MARK WITH RUN CODE

LAB LEAK CHECK (60 SEC PRESSURE CHANGE)
CHECK UNDER VACUUM (~8 IN. Hg)

INITIAL ______________________________ (IN. Hg)
FINAL ______________________________ (IN. Hg)

NOTES AND OBSERVATIONS

PERSON UNLOADING SAMPLER AND DATE UNLOADED

NOTE YOUR OBSERVATIONS ON THE APPEARANCE OF EACH STAGE, SUBSTRATE, OR CYCLONE UPON DISASSEMBLY

THIS FORM MAY BE USED FOR ANY OF THREE DIFFERENT TYPES OF SAMPLERS.
CIRCLE THE TYPE SAMPLER USED
MT FILTER   PM10   5 SERIES CYCLONE

MASS TRAIN FILTER (CIRCLE ONE)

- 47 MM FILTER
- 63 MM FILTER
- THIMBLE

FILTER ID NO. ______________
NOZZLE WASH ID NO. ______________

PM10 SAMPLER

CYCLONE 1
PM -CY

CYCLONE 2
PM -CY

FILTER
PM -F

5 SERIES CYCLONE SET

CYCLONE 1
CY -1

CYCLONE 2
CY -2

CYCLONE 3
CY -3

CYCLONE 4
CY -4

CYCLONE 5
CY -5

FILTER
CY -F

5850-430

Sheet I.D.______

WEIGHT SHEETS FOR USE WITH THE METTLER BALANCE

Substrate Set I.D. _________

PRE-TEST WEIGHTS

Operator ________________________
Date ____________________________
Calibration Check? ______________

I.D.	Weight (gm)	Offset (gm)	Actual (gm)

Operator ________________________
Date ____________________________
Calibration Check?______________

Weight (gm)	Offset (gm)	Actual (gm)	Final (gm)

FINAL WEIGHTS

Operator ________________________
Date ____________________________
Calibration Check? ______________

I.D.	Weight (gm)	Offset (gm)	Actual (mg)

Operator ________________________
Date ____________________________
Calibration Check? ______________

Weight (gm)	Offset (gm)	Actual (mg)	Final (mg)	Wt.Gain (mg)

Note: A control weight should be recorded at least every tenth weight.

Sheet I.D. _____

REAGENT BLANK EVALUATION FORM

Date: ______________________________
Operator: ______________________________
Reagent: ______________________________
I.D.#: ______________________________
Density (mg/ml) ______________________________

Barometric Pressure (in. Hg): ____________
Ambient Temperature (°F): ____________

In a tared weighing pan add a specified amount (20-30ml) of the reagent. Allow the solution to evaporate and reweigh the pan. The net weight gain shall be considered residue from the reagent.

NOTE: For each separate bottle or container of reagent a minimum of three blanks should be obtained to determine an average residue mass.

Pan I.D.	TARE (mg)	Volume Reagent (ml)	Final Weight (mg)	Mass Residue (mg)	% Impurities[a]
				Average[b]	

[a] $\% \text{ Impurities} = \frac{(\text{Residue, mg})}{(\text{Density, mg/ml})(\text{Volume, ml})} = \times 100\%$

[b] For reagents the average to impurities should be $<0.001\%$

APPENDIX D

HP41C SETUP PROGRAM FOR EGR SYSTEM (EGR SET)

The EGR setup program is used to determine the sample orifice, total flow LFE, and recycle flow LFE pressure differentials required to maintain isokinetic sampling for given stack conditions. The program uses an approximation of the total flow rate, Q_t, to eliminate the necessity of an iterative solution. This approximation agrees with the exact solution of the equation to ±1% for stack conditions in the range of 100 to 500 °F and 0 to 50% moisture. An additional approximation is introduced by assuming stack temperature to be constant at the average stack temperature. This approximation removes the complicated temperature dependence from all three pressure drop equations. Pressure drops calculated in this manner agree within ±10% with exact solutions for temperatures in the range of ±50 °F of the average.

Initial prompts for data input are as follows:

1) Barometric pressure
2) Static pressure of stack
3) Average stack temperature
4) Gas meter temperature
5) Dry molecular weight
6) Wet molecular weight
7) Percent oxygen
8) Percent moisture
9) Calibration constants
    - o S_t
    - o W_t
    - o S_r
    - o W_r

- Delta H_a
- Nozzle diameter
- Pitot C_p

After the above data are entered, the program calculates the equation constants for each of the pressure differentials, in the following form:

$$\Delta H = K\Delta p_{vel}$$

$$\Delta p_t = A_t - B_t \sqrt{\Delta p_{vel}}$$

$$\Delta p_r = A_t - B_t \sqrt{\Delta p_{vel}}$$

When the pressure differential equations have been determined, the program enters a short loop and prompts for the velocity pressure, Δp_{vel}. After entering this information, the sample orifice ΔH, total flow LFE Δp_t, and the recycle flow LFE Δp_r are determined. The program then asks if there are more traverse points. A "Yes" answer resets the program to the beginning of the loop. A "No" answer ends the program.

Note that if the stack temperature deviates from the average temperature entered by more than 50 °F, the equation constants should be recalculated by reentering the beginning of the program.

```
01◆LBL "EGR SET"
02  FIX 2
03  CLRG
04  "BAR PRESS?"
05  PROMPT
06  STO 01
07  .59
08  +
09  STO 06
10  "STATIC P INWG?"
11  PROMPT
12  13.6
13  /
14  RCL 01
15  +
16  STO 07
17  "STACK TEMP?"
18  PROMPT
19  STO 08
20  X↑2
21  3.2355 E-5
22  *
23  .25529
24  RCL 08
25  *
26  +
27  152.418
28  +
29  STO 09
30  "METER TEMP?"
31  PROMPT
32  STO 10
33  X↑2
34  3.2355 E-5
35  *
36  .25529
37  RCL 10
38  *
39  +
40  152.418
41  +
42  STO 11
43  460
44  ST+ 08
45  ST+ 10
46  "DRY MOL WT?"
47  PROMPT
48  STO 12
49  "WET MOL WT?"
50  PROMPT
51  STO 13
52  "%O2 ?"
53  PROMPT
54  .53147
55  *
56  ST+ 09
57  ST+ 11
58  "% MOISTURE?"
59  PROMPT
60  100
61  /
62  STO 14
63  "CALIBRATION"
64  AVIEW
65  PSE
66  "DATA"
67  AVIEW
68  PSE
69  "XT ?"
70  PROMPT
71  STO 15
72  "YT ?"
73  PROMPT
74  STO 16
75  "XR ?"
76  PROMPT
77  STO 17
78  "YR ?"
79  PROMPT
80  STO 18
81  "DELTA Ha?"
82  PROMPT
83  RCL 01
84  /
85  STO 01
86  "DIA NOZZLE?"
87  PROMPT
88  X↑2
89  STO 19
90  X↑2
91  ST* 01
92  "PITOT CP?"
93  PROMPT
94  ST* 19
95  X↑2
96  ST* 01
97  1
98  RCL 14
99  -
100  X↑2
101  ST* 01
102  RCL 12
103  ST* 01
104  RCL 10
```

```
105  ST* 19
106  ST* 01
107  RCL 07
108  ST* 01
109  SQRT
110  ST* 19
111  RCL 13
112  ST/ 01
113  RCL 08
114  ST/ 01
115  SQRT
116  ST/ 19
117  846.72
118  ST* 01
119  LDL 01
120  RCL 11
121  ST* 19
122  RCL 06
123  ST/ 19
124  .1539
125  ST* 19
126  18
127  RCL 12
128  /
129  1
130  X<>Y
131  -
132  .2949
133  *
134  1
135  X<>Y
136  -
137  RCL 09
138  *
139  RCL 14
140  *
141  STO 03
142  1
143  RCL 14
144  -
145  RCL 14
146  *
147  74.143
148  *
149  ST+ 03
150  RCL 09
151  RCL 14
152  74.143
153  *
154  -
155  ST/ 03
156  RCL 19
157  RCL 15
158  /
159  RCL 13
160  SQRT
161  /
162  ST* 03
163  RCL 11
164  RCL 10
165  *
166  RCL 07
167  .7051
168  Y↑X
169  *
170  RCL 09
171  *
172  RCL 06
173  /
174  RCL 12
175  .2949
176  Y↑X
177  /
178  RCL 08
179  .7051
180  Y↑X
181  /
182  1.5752 E-5
183  *
184  STO 20
185  RCL 11
186  180.1
187  /
188  RCL 16
189  *
190  RCL 20
191  X<>Y
192  -
193  RCL 15
194  /
195  STO 02
196  LBL 02
197  RCL 17
198  ST/ 19
199  RCL 09
200  RCL 14
201  74.143
202  *
203  -
204  RCL 09
205  X<>Y
206  /
207  RCL 12
208  .2949
```

```
209  Y↑X
210  /
211  RCL 13
212  .2051
213  Y↑X
214  /
215  RCL 19
216  *
217  STO 05
218  RCL 11
219  180.1
220  /
221  RCL 18
222  *
223  RCL 20
224  X<>Y
225  -
226  RCL 17
227  /
228  STO 04
229 ◆LBL 03
230  "VELOCITY DP?"
231  PROMPT
232  STO 00
233  RCL 01
234  *
235  "DELTA H= "
236  ARCL X
237  AVIEW
238  PSE
239  RCL 00
240  SQRT
241  RCL 03
242  *
243  RCL 02
244  X<>Y
245  -
246  "DP TOTAL = "
247  ARCL X
248  AVIEW
249  PSE
250  RCL 00
251  SQRT
252  RCL 05
253  *
254  RCL 04
255  X<>Y
256  -
257  "DP RECYCLE = "
258  ARCL X
259  AVIEW
260  PSE
261  AON
262  "MORE PTS? Y,N"
263  PROMPT
264  ASTO Y
265  AOFF
266  "Y"
267  ASTO X
268  X=Y?
269  GTO 03
270  CLX
271  END
```

GLOSSARY

Aerodynamic diameter: The aerodynamic diameter of a particle is the diameter of a sphere of unit density whch has the same settling velocity in the gas as the particle of interest. For spherical particles with diameter Dp, larger than a few microns and gas conditions of interest for source PM_{10}, the aerodynamic diameter is essentially given by $\sqrt{\rho_p}\, D_p$ where ρ_p is the particle density.

Cut-point: The cut-point of a size classifier is the particle diameter for which all particles of equal or greater diameter are captured and all particles with smaller diameters are not captured. No real device actually has a sharp step function cut-point, but the theoretically defined D_{50} of a stage is often called its cut-point.

Geometric standard deviation, σ_g: A measure of dispersion in a lognormal distribution. It can be calculated as the ratio of particle diameter corresponding to a cumulative percent of 50 to the diameter corresponding to a cumulative percent of 15.86.